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Sensitivity of multi-coil frequency domain electromagnetic induction sensors to map soil magnetic susceptibility

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Summary

Magnetic susceptibility is an important indicator of anthropogenic disturbance in the natural soil. This property is often mapped with magnetic gradiometers in archaeological prospection studies. It is also detected with frequency domain electromagnetic induction (FDEM) sensors, which have the advantage that they can simultaneously measure the electrical conductivity. The detection level of FDEM sensors for magnetic structures is very dependent on the coil configuration. Apart from theoretical modelling studies, a thorough investigation with field models has not been conducted until now. Therefore, the goal of this study was to test multiple coil configurations on a test field with naturally enhanced magnetic susceptibility in the topsoil and with different types of structures mimicking real archaeological features. Two FDEM sensors were used with coil separations between 0.5 and 2 m and with three coil orientations. First, a vertical sounding was conducted over the undisturbed soil to test the validity of a theoretical layered model, which can be used to infer the depth sensitivity of the coil configurations. The modelled sounding values corresponded well with the measured data, which means that the theoretical models are applicable to layered soils. Second, magnetic structures were buried in the site and the resulting anomalies measured to a very high resolution. The results showed remarkable differences in amplitude and complexity between the responses of the coil configurations. The 2-m horizontal coplanar and 1.1-m perpendicular coil configurations produced the clearest anomalies and resembled best a gradiometer measurement.

Introduction

Anthropogenic disturbances of the natural soil volume often cause local changes in the magnetic susceptibility (Clark, 1990). In most archaeological prospections, a magnetometer is used to measure these contrasts. However, frequency domain electromagnetic induction (FDEM) sensors with 'slingram' geometry are also capable of measuring the magnetic susceptibility by using the in-phase (IP) response of the ratio of the secondary to the primary electromagnetic field. These sensors can also measure the soil electrical conductivity by using the quadrature-phase (QP) response, which is an additional advantage for archaeological prospection.

Although the measurement of the magnetic susceptibility with FDEM sensors was explored decades ago (Tabbagh, 1990), most archaeological prospections use the QP response of the FDEM sensors without considering the IP response. A possible reason for this is the difficult interpretation of the IP signal, which can produce completely different results depending on the coil configuration of the instrument and the depth of the target (Linford, 1998; Simpson *et al*., 2009). Another difficulty is the occurrence of both positive and negative anomalies for some coil configurations, which are related to a change in sign of the IP response at a certain depth (Tabbagh, 1986). However, when the response of the different coil configurations is well understood, it can be used to deduce the magnetic susceptibility variation in the soil profile (Dalan & Bevan, 2002).

Wait (1955, 1962) derived the FDEM responses as a function of depth for a homogeneous medium and these equations were further approximated for the QP (McNeill, 1980) and the IP responses (Geonics Limited, 1998, based on Keller & Frischknecht, 1966). In the restricted conditions of a low induction number (IN), the approximate functions were also claimed to be valid for layered media. Because of their simple, analytical form, the conductivity models have been applied frequently in soil science to reconstruct the soil profile, with good results (Hendrickx *et al*., 2002; Saey *et al*., 2008). However, case studies using the depth-sensitivity models applied to a layered soil with varying magnetic

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susceptibility are rare. Therefore, it is not certain that these models are accurate enough to describe field measurements.

Structures with horizontal dimensions in the range of the coil separation cannot be modelled using a layered approach; in this case 3-D models are necessary that take lateral variations into account (Guérin *et al*., 1996). The effect of the coil orientation for a coil separation of 1.5 m was evaluated using theoretical 1-D and 3-D models, where the perpendicular (PERP) and vertical coplanar (VCP) orientations had a deeper exploration depth for the magnetic response than the horizontal coplanar (HCP) orientation (Tabbagh, 1985, 1986). In another study, both theoretical modelling and a field model were used to conclude that the magnetic response of 'slingram'-type FDEM sensors was less influenced by the soil electrical conductivity and had a better depth response than coincident loop instruments (Benech & Marmet, 1999). These studies were largely based on theoretical modelling, because building prototype sensors and testing them on representative field models is difficult. Recently, however, FDEM-sensors with multiple coil separations and orientations have been developed, making a detailed field study possible. No such comparison between different sensor configurations has been performed until now.

This study aimed to test the spatial sensitivity of different coil configurations of FDEM sensors measuring the magnetic susceptibility. Both a layered soil model and small structures were investigated, but this excluded metal objects. For this purpose, field measurements were conducted on an experimental site with magnetic structures of different sizes and shapes, resembling typical archaeological features. The response of the undisturbed soil was simulated on the basis of the analytical, layered models. With this experiment, the goal was to answer two specific research questions. First, are the theoretical, layered models well correlated with the field measurements for different coil configurations? Second, what is the sensitivity of each coil configuration for both layered soils and 3-D artefacts?

Experimental set-up

The test site was located at the Institute of Vegetable and Ornamental crops in Grossbeeren (Germany). The soil consisted of glacial till deposits, dominated by coarse sand. Therefore, the electrical conductivity was in general very low, less than 10 mS m^{-1}. This was important because high conductivities can influence the IP response of the FDEM sensors (Benech & Marmet, 1999). A test strip of 200 m × 10 m at the site was reserved for geophysical tests. Before the measurements, the soil surface was smoothed with a shallow cultivator to reduce the noise caused by instability while moving the sensors.

Two FDEM sensors were used: the DUALEM-21S (Dualem Inc., Milton, Canada) and the EM38-MK2 (Geonics Limited, Mississauga, Canada). Both sensors have one transmitter coil with a fixed frequency of 9 kHz (DUALEM-21S) or 14.5 kHz (EM38-MK2, Figure 1). The DUALEM-21S has four receiver coils: two in a horizontal coplanar (HCP) orientation, at a distance of 1 and 2 m from the transmitter (1HCP and 2HCP), and two in perpendicular arrangement, at 1.1 and 2.1 m from the transmitter (1.1PERP and 2.1PERP). The EM38-MK2 has two receivers in HCP orientation, at 0.5 and 1 m separation (0.5HCP and 1HCP). When the sensors are turned 90° around their long axis, the vertical coplanar (VCP) orientation can be measured (0.5VCP, 1VCP and 2VCP). Both sensors record the IP as well as the QP response of the secondary field at the receiver coil in respect of the primary field and are designed to operate under low induction-number (IN) conditions. The IN is defined as the coil separation divided by the 'skin' depth or the depth where the wave amplitude is reduced to 1/*e* (McNeill, 1980). When the IN is low, the IP response is proportional to the soil apparent magnetic susceptibility ($\chi_{a,}$ expressed in volumetric SI units throughout) and the QP response is proportional to the soil apparent electrical conductivity (σ_a). The χ_a values were calculated from the IP output with the following equation (Geonics Limited, 1998):

$$\chi_a = 2 \times 0.001 \times (H_s/H_p)_{IP}. \tag{1}$$

The factor 0.001 converts the output in parts per thousand to the ratio of the secondary field (H_s) over the primary field (H_p).

It is important to estimate the noise level of the FDEM sensors before evaluating their sensitivity. The noise can be caused by instrumental, environmental or operational factors, making it difficult to obtain a single noise level. Nevertheless, the noise was estimated by recording the sensor output for 25 minutes on a fixed position at the experimental site and calculating the standard deviation (Table 1). The highest standard deviation was 3.4×10^{-5} (SI).

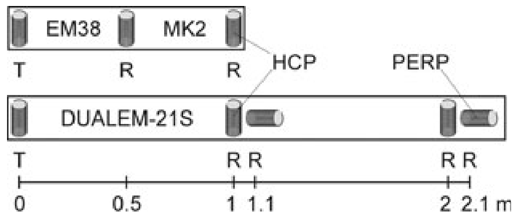

Figure 1 Coil configurations of the FDEM sensors. The VCP are the same as those for HCP when the sensors are turned 90° around their long axis.

Table 1 Standard deviations of the FDEM measurements at a fixed position

Sensor type	EM38-MK2	
Configuration	1HCP	0.5HCP
χ_a / 10^{-5} SI	3.395	0.685
Sensor type	DUALEM-21S	
Configuration	1HCP	1.1PERP
χ_a / 10^{-5} SI	0.910	0.799
Configuration	2HCP	2.1PERP
χ_a / 10^{-5} SI	3.166	3.109

Vertical sounding on a layered soil

Theoretical models

Assuming a very small IN, the IP response for a homogeneous halfspace with zero conductivity but with a certain magnetic permeability can be derived by using the image method as a function of the coil separation and the height above the halfspace (the soil surface; Keller & Frischknecht, 1966). It has been stated that if the operating frequency is small enough, 'the magnetic interaction between all secondary induced magnetic dipoles can be ignored' (Geonics Limited, 1998), which means that the magnetic susceptibility of one layer does not influence the IP response of another. Consequently, the equations for a homogeneous halfspace can be extended to layered media. Moreover, if the sensor is raised above the soil surface (in geophysical terms called a 'vertical sounding'), one of the layers is the air between the sensor and the soil. The same equations can therefore be applied to vertical soundings, assuming that the top layer consists of air with a χ of 0 (SI). The equations of Keller & Frischknecht (1966), expressed as the cumulative weight C of the soil χ from an infinite depth up to a certain depth z for a coil separation s are:

$$C(HCP, z, s) = \frac{1 - 8(z/s)^2}{(4(z/s)^2 + 1)^{5/2}}, \tag{2}$$

$$C(VCP, z, s) = \frac{1}{(4(z/s)^2 + 1)^{3/2}}, \tag{3}$$

$$C(PERP, z, s) = \frac{6(z/s)}{(4(z/s)^2 + 1)^{5/2}}. \tag{4}$$

Differentiation of these equations with respect to z yields the relative weight R of an infinitesimally thin layer to the total response:

$$R(HCP, z, s) = \frac{12(z/s)\cdot(3 - 8(z/s)^2)}{s(4(z/s)^2 + 1)^{7/2}}, \tag{5}$$

$$R(VCP, z, s) = \frac{12(z/s)}{s(4(z/s)^2 + 1)^{5/2}}, \tag{6}$$

$$R(PERP, z, s) = \frac{96(z/s)^2 - 6}{s(4(z/s)^2 + 1)^{7/2}}. \tag{7}$$

According to Geonics Limited (1998), these equations can be used to model the expected χ_a of a layered medium:

$$\chi_a = \sum_i \chi_i (C_i - C_{i-1}), \tag{8}$$

where χ_i is the magnetic susceptibility of layer i, C_i is the cumulative weight at the top of layer i and C_{i-1} is the cumulative weight of the bottom of layer i. As well as modelling the expected IP measurement, these models can be plotted to estimate the sensitivity of the coil configurations for soil layers with a specific χ_i at different depths (Figure 2).

Modelling versus field measurements

To test the validity of the theoretical models for layered soils, a vertical sounding was conducted on an undisturbed soil with the DUALEM-21S in the HCP and PERP orientations and with the EM38-MK2 in the VCP orientation. The χ_i of the soil profile was determined in a freshly dug pit near to the sounding location with a hand-held meter (Kappameter KT-6, SatisGeo, Brno, Czech Republic). The profile was measured several times at 0.1-m intervals down to 0.8 m, measuring the χ_i at the contact surface of the sides and the bottom of the pit (Figure 3). These values were then used to model the χ_a values of the vertical soundings. The soil profile was divided into layers of 0.1 m according to the depths of the hand-held measurements. The bottom of the deepest layer was assumed to be at infinite depth. The contribution of each layer to the total χ_a of the soil was calculated using Equation (8).

The IP measurements of a FDEM sensor can suffer from serious drift. This drift has been attributed to changes of the resistance or capacitance of the electronic components in the sensor caused by temperature changes (Keller & Frischknecht, 1966). This disturbed the vertical sounding measurements in two ways; the absolute values were different when the sounding was initiated and the measurements were changed during the sounding. To verify if any drift occurred during the sounding, each profile was measured from 2-m height down to 0 m and then repeated from 0 to 2-m height (Figure 4). The drift was large relative to the sounding values, so it required correction. Therefore, two repeated readings at the same height were averaged to remove the drift. Then, to correct the absolute value error, the measurements were all shifted with a constant value, so that the readings at 2 m corresponded with the modelled values.

The simulated sounding curves based on the profile values of Figure 2 were strongly related to the measured values obtained with the two sensors (Figure 5). The coil orientation with the best relationship was the HCP. The PERP orientation was more noise sensitive, which explains why the measured values were less precisely represented by the modelled curves. The measurements of the 1.1PERP were significantly larger than the curve for shallow layers. The VCP showed a slight decrease of the measured values between 0.5 and 1.5 m for both coil separations, which was not followed by the model curves.

Thus, in general, the results indicated that the approximate models of Keller & Frischknecht (1966) follow closely the measured soundings in this low-conductive environment. Therefore, these analytical functions can be used to infer the depth sensitivity of the magnetic signals of FDEM sensors with different coil configurations. The change in sign from positive in shallow layers to negative in deeper layers in the HCP orientation has been noted by Tabbagh (1986) as being problematic for the depth response.

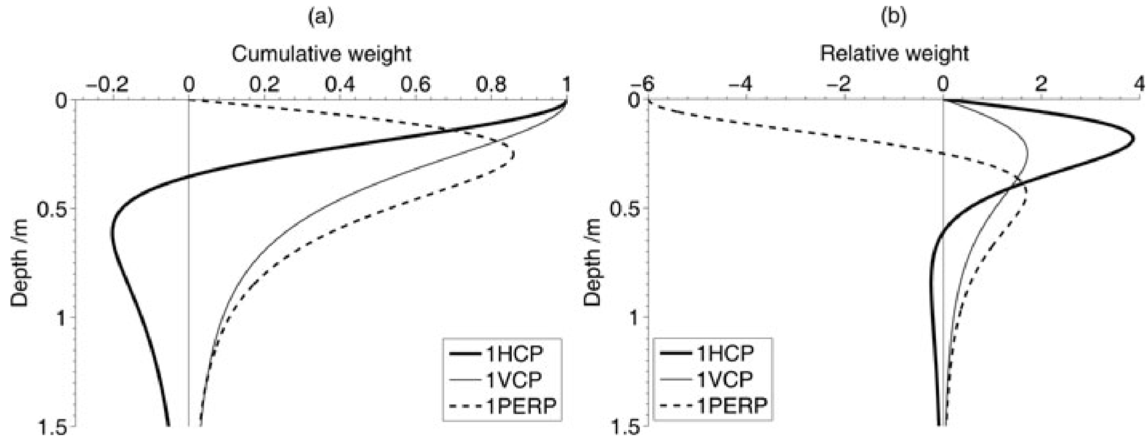

Figure 2 Theoretical response curves for a 1-m coil separation in three coil orientations; (a) cumulative weight of all layers below a specific depth and (b) relative weight of a thin layer.

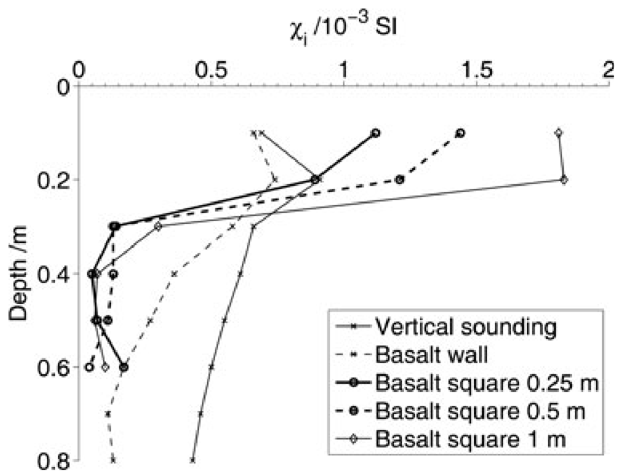

Figure 3 Magnetic susceptibility of different soil profiles at the test site, measured with a hand-held meter. The freshly-dug profiles were used where the structures were buried afterwards (the names of the structures are as noted on the Figure).

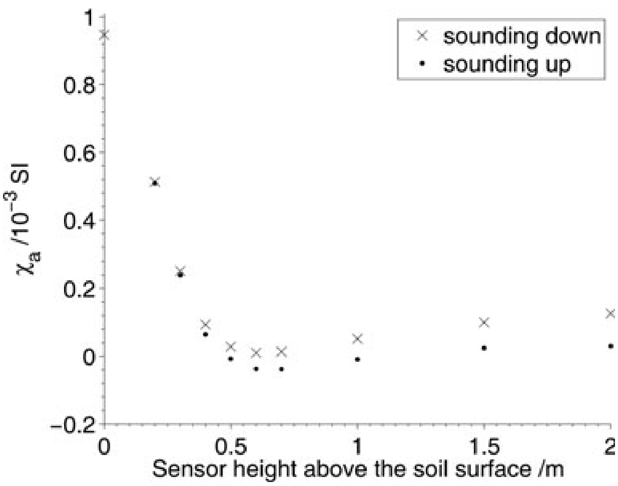

Figure 4 Difference between the 1-m HCP sounding measurements, measured from 2-m height downwards to 0 m and then back upwards to 2 m. The longer the time between two readings at the same height, the greater the difference due to the drift.

The coil separation has an influence on the depth where this sign change occurs, which was illustrated by a case-study reported in Simpson *et al*. (2009). The PERP orientation also demonstrated a similar sign change, which was not noted by Tabbagh (1986). It occurred at a shallower depth than the HCP response for an equal coil separation. It is often proposed to lift the instrument above the inflection point so that the sign change is effectively cancelled. However, lifting the sensor can considerably reduce the signal to noise ratio of the configurations with shallow depth sensitivity.

Sensitivity to small 3-D structures

Field models of locally increased magnetic susceptibility

Four structures were buried in the test site, to approximate as closely as possible typical magnetic anomalies of archaeological interest, but excluding metallic artefacts. The structures consisted of basalt stone powder, with a relatively large χ (0.01 SI) compared with that of the average soil (in the order of 0.0005 SI, Figure 3) and a σ of 50 mS m^{-1} (soil σ < 10 mS m^{-1}). First, a pit 0.8 m deep, 5 m long and 0.5 m wide was dug perpendicular to the test strip, filled with the basalt up to 0.3-m depth and then the remaining 0.3 m was filled by the original topsoil. In this way, any change in the topsoil χ was minimized. This structure mimicked linear artefacts often found at archaeological sites such as remains of walls, ditches and roads. Therefore, throughout the article this structure is referred to as the 'basalt wall'. In agricultural fields, the topsoil is commonly disturbed to a depth of 0.3 m by ploughing, so that most surviving artefacts are found just under the plough layer. Before the pit was refilled, hand-held measurements of χ were made at the bottom and sides of the pit surface at different

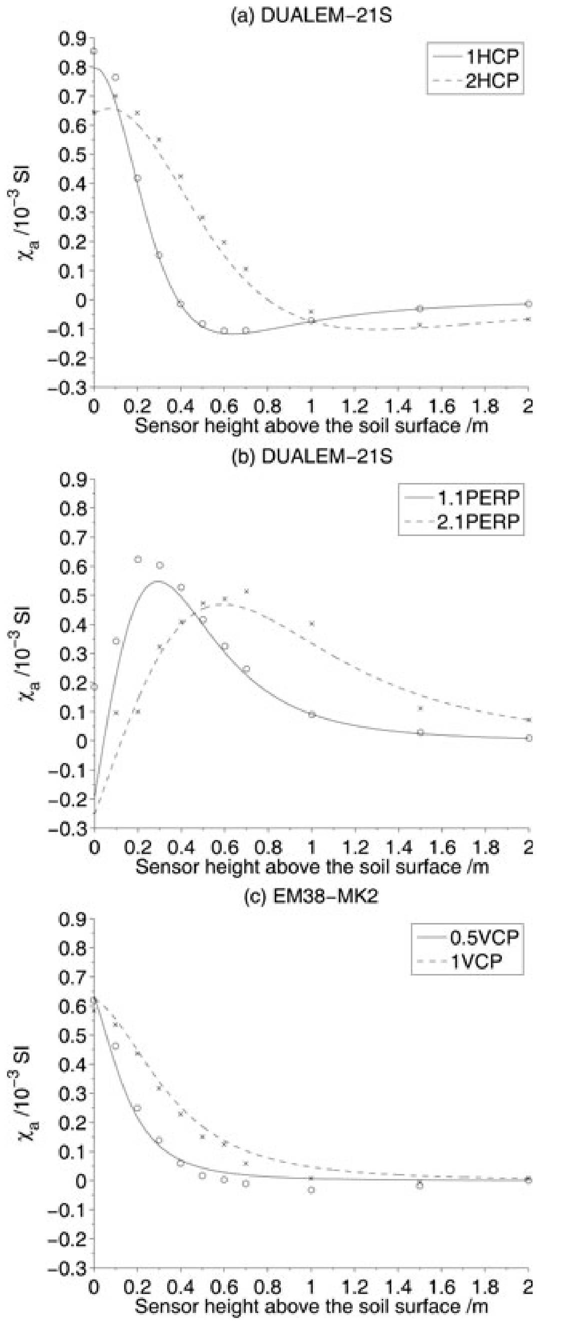

Figure 5 Vertical sounding measurements (symbols) and theoretical models (lines). (a) HCP orientation of the DUALEM-21S, (b) PERP orientation of the DUALEM-21S and (c) VCP orientation of the EM38-MK2.

depths. After filling the pit with basalt and refilling the topsoil, the χ was measured at the surface with the hand-held meter. Although the topsoil above the feature was mixed after the filling, the average χ after mixing approximated that of the undisturbed profile. The basalt powder was not held in any container, so it was in direct contact with the surrounding soil. After some time, the structures would probably not remain intact because of, for example, bioturbation, but the measurements in this study were conducted within days after the structures were built and so remained intact.

Three other structures were buried using the same procedure as the basalt wall, but with other dimensions. They were chosen to act as models for smaller artefacts such as a fire place or a garbage pit. All three structures were square and were 0.3 m thick, and started at 0.3-m depth: they were 1×1 m, 0.5×0.5 m and 0.25×0.25 m. These structures are referred to as 'basalt squares'. The positions of the basalt wall and squares were determined with a differential GPS (with an absolute accuracy of approximately 0.2 m).

Measurements were conducted with the DUALEM-21S and the EM38-MK2 on a cart, which was pushed at walking speed and geo-referenced with the dGPS. The cross-line distance was 0.25 m for the basalt squares and 0.5 m for the basalt wall. The inline measurement distances were on average 0.1 m. Both sensors were positioned at 0.2 m above the soil surface, thus 0.5 m from the top of the structures. One survey was also conducted with the DUALEM-21S at 0.5-m height in HCP-PERP orientation, so that the distance to the top of the structures increased to 0.8 m. All measurements were processed with the same procedures: (i) correction of the offset between the GPS antenna and the midpoint of the sensor coils, (ii) noise filtering using a local search window, (iii) interpolation with ordinary kriging to a grid with a 0.1 by 0.1 m cell size and (iv) subtraction of the average background value (based on pixels at least 2 m away from the edges of the structures).

Finally, the site was also prospected with a Fluxgate gradiometer (type FM18, Geoscan, Bradford, UK), by measuring the 0.5 m vertical magnetic gradient (expressed in nT/0.5 m). The instrument was operated manually, holding it at waist-height. The survey lines were laid out with tapes at a 0.5 m distance and measurements were recorded inline every 0.5 m distance at the basalt wall and every 0.25 m at the position of the basalt squares. This sensor is often used in archaeological prospection and therefore served to evaluate the detection limits of the FDEM sensors.

Results of the field measurements

The magnetic susceptibility was greater in the organic topsoil for all five soil profiles (Figure 3), which is a naturally occurring phenomenon (Scollar, 1990). The profiles varied from smoothly declining values at depth to a sharp decrease between 0.2 and 0.3 m depth.

The different sensor configurations showed very different responses to the basalt wall (Figure 6). The detection quality was based on three criteria: (i) maximum absolute deviation from the background value, (ii) width of the anomaly parallel to the sensor and through the middle of the basalt wall, delineated by a detection level of 0.0001 SI (more than twice the noise level of the sensors) and (iii) complexity of the response, evaluated by the sign (change) and asymmetry of the response.

The maximum absolute deviation was observed on the transects in the middle of the wall and in the middle of the basalt squares

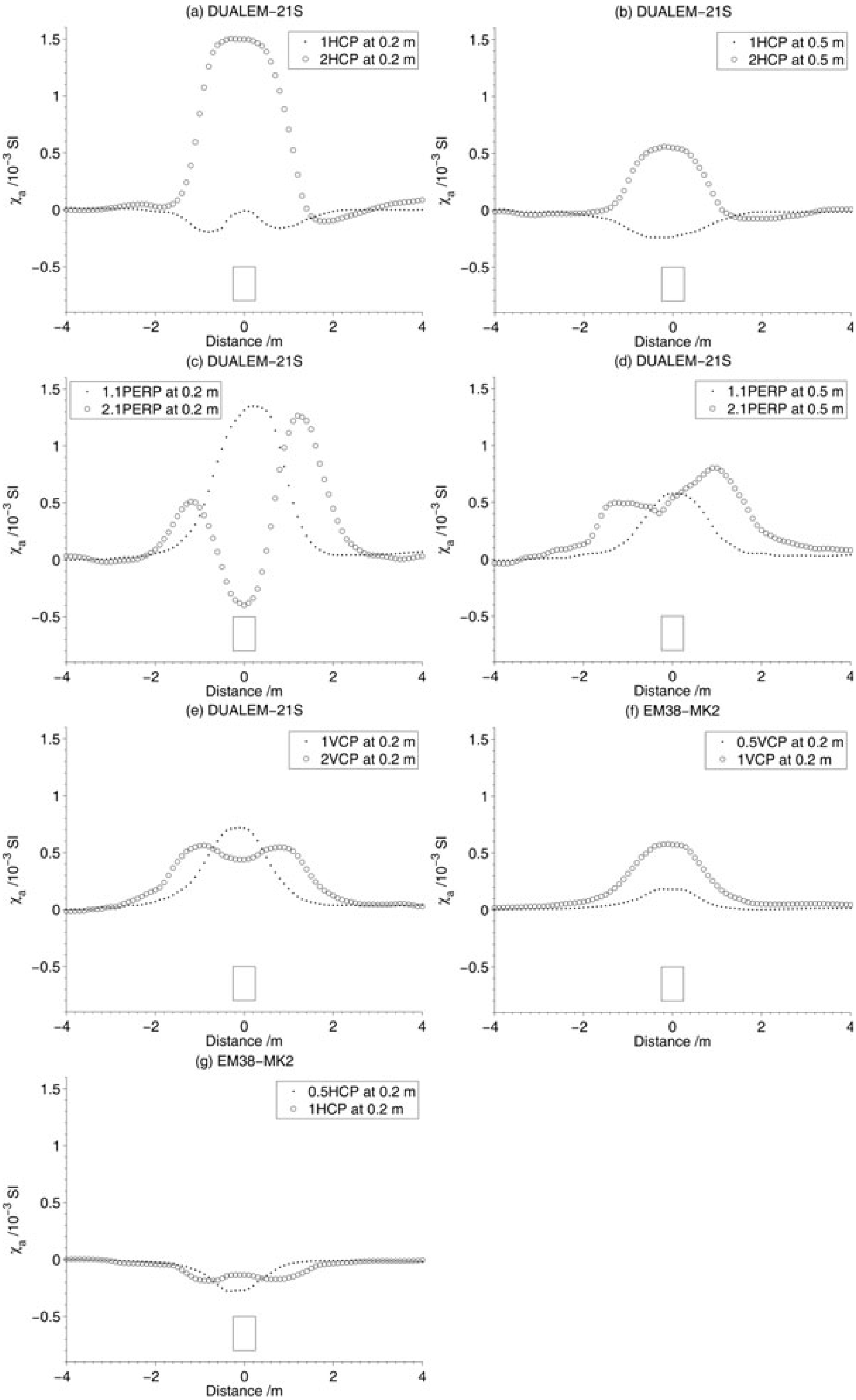

Figure 6 Transect through the middle of the basalt wall. The rectangle indicates the position and dimension of the wall in the horizontal, but not in the vertical, direction.

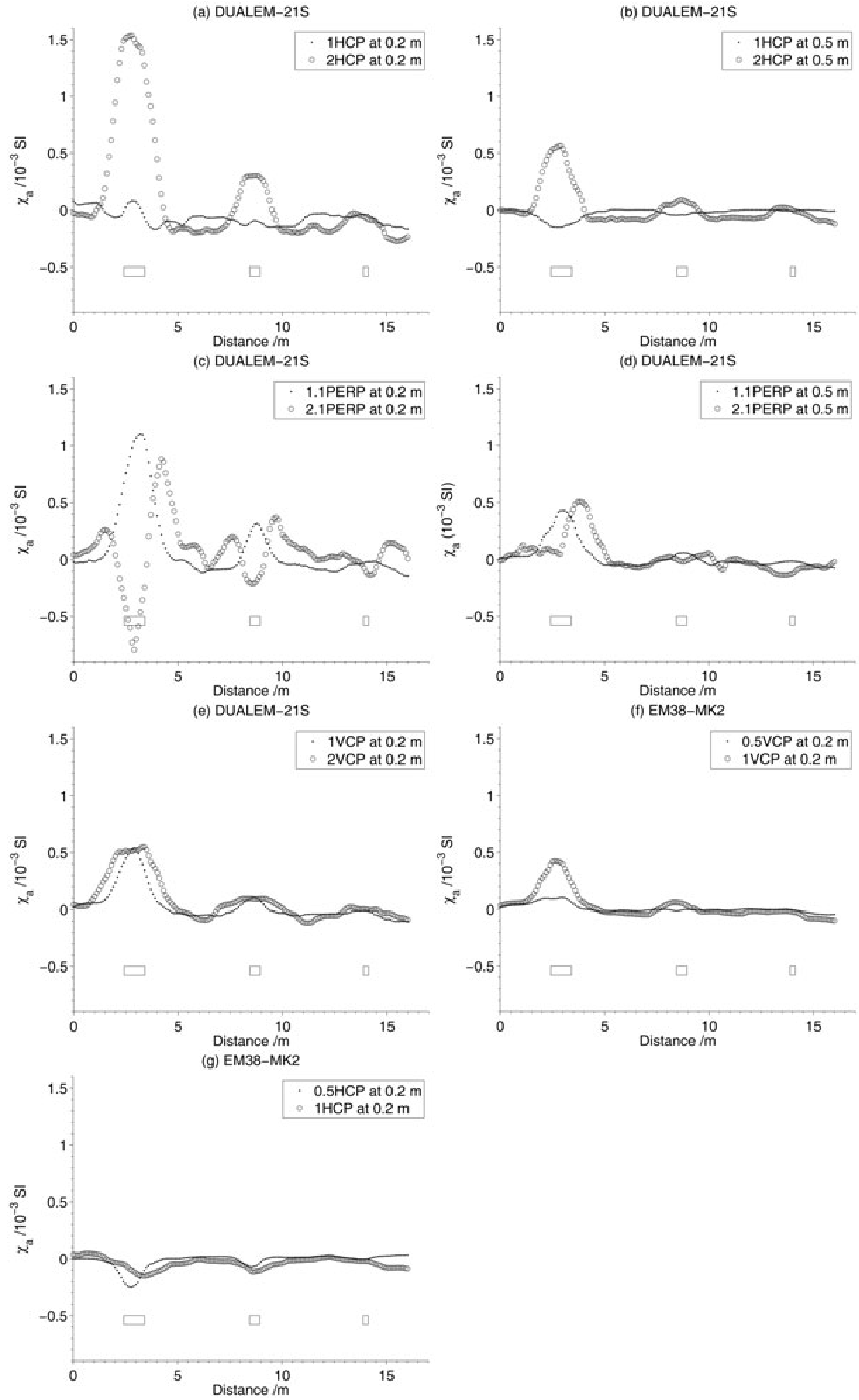

Figure 7 Transect through the middle of the basalt squares. The rectangle indicates the position and dimension of the squares in the horizontal, but not in the vertical, direction.

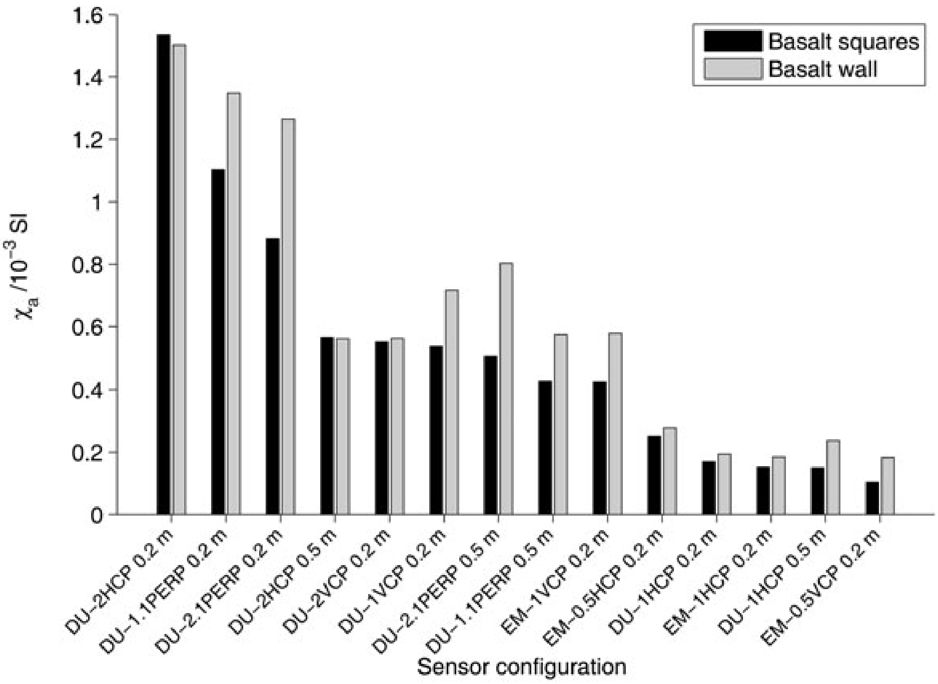

Figure 8 Maximum absolute deviation from the background χ_a for the different sensor configurations. The abbreviations EM and DU refer to the EM38-MK2 and DUALEM-21S sensors.

(Figures 6 and 7). These values were then ranked for the different configurations (Figure 8). The overall order of the configurations was similar for the basalt squares and the basalt wall. The 2HCP, 1.1PERP and 2.1PERP configurations at 0.2-m height produced the largest deviation. The 1VCP and 2VCP responses had intermediate deviations and the 1HCP, 0.5HCP and 0.5VCP configurations produced weak responses to the basalt wall. An important finding was that the HCP configurations had the strongest response for the 2-m coil separation but the smallest for the 1-m and 0.5-m coil separations after the 0.5VCP. The sensor responses were also ranked on the basis of the second criterion, which is a measure of the compactness of the anomaly (Table 2). A more compact anomaly will result in a sharper delineation of the structures. Except for the DU2HCP, the larger coil separations had a wider anomaly in the direction that was parallel to the sensor. Overall, the HCP orientation was more compact than the VCP and the VCP was more compact than the PERP.

The third criterion can be evaluated visually from the transects shown in Figures 6 and 7. The 2.1PERP anomaly was asymmetric and changed sign over the structures, making it more difficult to interpret. This is in accordance with Tabbagh (1986), who investigated a 1.5-m PERP configuration at 0.15-m height. In contrast, the 1.1PERP anomaly was symmetric and did not show any change of sign at either height. Both the VCP and HCP anomalies were symmetric, as expected. The HCP orientation displayed a sign change at 0.2-m height for the small coil separations of 0.5 and 1 m, while the sign change was negligible for the 2-m separation. This probably explains the very weak response of the small

Table 2 Horizontal width of the basalt wall anomalies for the different sensor configurations

Coil configuration	Sensor height / m	Anomaly width / m	Coil configuration	Sensor height / m	Anomaly width / m
EM-0.5VCP	0.2	1.4	EM-1HCP	0.2	2.8
EM-0.5HCP	0.2	1.7	DU-1VCP	0.2	3.0
DU-2HCP	0.5	2.2	EM-1VCP	0.2	3.2
DU-1HCP	0.5	2.4	DU-1.1PERP	0.2	3.3
DU-1HCP	0.2	2.6	DU-2VCP	0.2	4.4
DU-1.1PERP	0.5	2.7	DU-2.1PERP	0.2	4.5
DU-2HCP	0.2	2.8	DU-2.1PERP	0.5	5.5

coil separations compared with the 2-m separation. For layered media, the response of a shallow structure can be partly positive and partly negative, so that they cancel each other out. Raising the instrument to a certain height can eliminate the positive response (see Figure 6b for the sensor height of 0.5 m above the soil surface), but this also reduces the overall signal to noise of the response.No sign change occurred in the VCP orientation, but the largest coil separation (2 m) showed two maxima instead of one.

Finally, the maps of all the sensor configurations were plotted using the same scale (Figure 9). This allowed us to evaluate the anomalies visually in two dimensions. At 0.2-m height, the 2HCP and 1.1PERP configurations appeared to give the clearest response to the basalt squares. The 2.1PERP response was very strong, and even detected the square structure with a 0.25-m

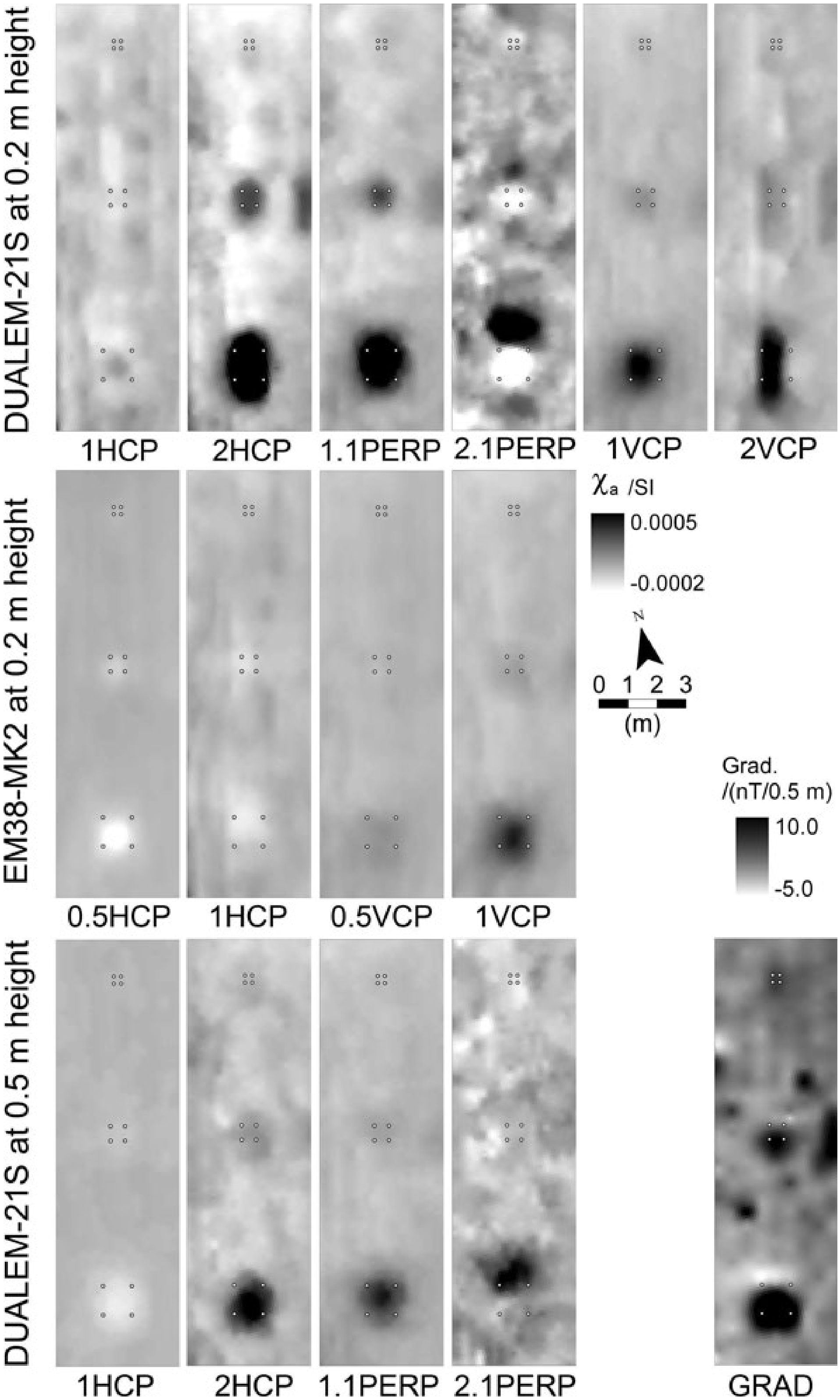

Figure 9 Maps of the FDEM configurations, at the same scale, and of the gradiometer readings. The corners of the three basalt squares are indicated by dots.

width, but its anomalies were complicated by positive and negative responses. The 1VCP anomaly was weaker but was very compact and well-centred on the location of the structure. The 2VCP anomaly was elongated in the sensor direction. At 0.5-m height, the 1HCP was more successful in detecting the structures, because the positive response was eliminated, which strengthened the negative response. The 2HCP and 1.1PERP were able to detect the 1-m and 0.5-m basalt squares. The 0.25-m square was only weakly visible. Overall, raising the instrument, and thus increasing the distance to the structure, seriously reduced the detection level.

The gradiometer detected the basalt squares well, but also here the smallest structure was less clear. As expected from gradiometer surveys at latitude 51° north, the positive anomaly was slightly shifted to the south, accompanied by a small negative anomaly to the north. Apart from the anomalies that were caused by the basalt squares, there were some other anomalies visible on the gradiometer map of unknown origin, for example to the east of the square structure that was 0.5 m wide. Considering these anomalies, the 2HCP map was closest to that from the gradiometer measurements.

Conclusions

Because the layered models fitted well with the measured vertical soundings of the FDEM sensor configurations, they can be used to describe the depth sensitivity of each configuration. An important aspect of the IP measurement is the sign change that occurred with both the HCP and PERP orientation at a depth depending on the coil separation. For the HCP, this sign change seems to be most affected at small coil separations, while the 2-m separation was less affected. The VCP response was entirely positive, making the interpretation of the anomaly much easier.

The detection of small archaeological structures with a magnetic susceptibility contrast was highly variable between different coil configurations of the FDEM sensors. The theoretical calculation of the responses gave similar results to the field measurements for the HCP response, but was less accurate for the PERP configuration. Therefore, the field measurements were used to evaluate the sensitivity of the sensor configurations. Taking into account different criteria for the quality of the anomalies, the 2HCP and 1.1PERP configurations gave the best results. These configurations were the only ones to have an output that was on a par with the gradiometer measurements. The HCP orientation with the smaller coil separations was very poor in detecting the structures. The VCP configurations showed a symmetric and one-directional response, but the anomaly of the 2VCP configuration was relatively wide.

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