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Exploring the potential of multi-receiver EMI survey for geoarchaeological prospection: A 90 ha dataset

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ABSTRACT

The archaeological evaluation of landscapes in the framework of developer-led archaeology is often based on extensive trenching programmes complemented with auger surveys in wetland environments. During the archaeological evaluation of a 90 ha polder site in the north-west of Belgium, a mobile multi-receiver electromagnetic induction (EMI) survey was used as a main prospecting technique. The use of a mobile survey allowed to map the entire study area at a very fine resolution (over 25 measurements per m^2). Incorporating a multi-receiver EMI instrument enabled measuring the apparent electrical conductivity (ECa) and the apparent magnetic susceptibility (MSa) of four different soil volumes simultaneously at each location. The detailed maps provided insight into the archaeological and geomorphological features of the site. Among the detected structures were a large medieval farmstead, a palaeoriver system and a number of military remains from World War I (WWI). The vertical discrimination potential added insight into the vertical facies changes, which allowed modeling the palaeolandscape and helped determining the depth of detected medieval features. The different MSa measurements gave additional insight into the WWI structures. In this paper, we give an overview of the possibilities of combining multiple ECa measurements for interpreting vertical soil variability together with an example of the added information from simultaneously gathered MSa data. More generally, the diverse potential of multi-receiver EMI survey for geoarchaeological research is demonstrated.

1. Introduction

The archaeological evaluation of large sites is becoming more common and standardized as government regulations to preserve national heritage are intensified in many countries. Such evaluation programs aim to determine the archaeological potential of land preparation sites in an early planning stage by desktop studies and field surveys. Of primary importance in these studies is the detection of archaeological features and the detection and reconstruction of buried landscapes (De Clercq et al., 2011; Lehouck et al., 2007). Common field methods to support these evaluations are mostly limited to extensive trenching programmes and hand augerings. Trial-trenches, for example, complemented with smaller window trenches covering a 15% of the surveyed surface have proven valuable tools in assessing the archaeological potential of uncovered landscapes (De Clercq et al., 2011). Although these methods offer a high local resolution, i.e. at sample locations, and allow detailed interpretation of detected features, they remain time and energy-consuming.

The introduction of near surface geophysical prospection methods has opened new perspectives for archaeological field evaluation (Gaffney and Gater, 2003; Kvamme, 2003). These methods can offer detailed and, when mobile, continuous information about the soil and deeper layers in a non-destructive way. However, the application of these techniques for archaeological prospections remains limited and only a few countries (e.g. United Kingdom (Jones, 2008)) have incorporated geophysical methods in standard evaluation procedures. Today, the main geophysical techniques used in archaeology are magnetometry, electrical resistance and ground penetrating radar (GPR) (Jordan, 2009; Viberg et al., 2011). The large-scale application of electromagnetic induction (EMI), on the other hand, remains rare in archaeological research (exceptions include Conyers et al. (2008), Lück and Eisenreich (1999) and Simpson et al. (2008)). This can partly be attributed to unsatisfying results with the first types of commercially available EMI sensors (e.g. the Geonics EM38) as these did not match up to the results and detecting resolution of the widely used electrical resistance instruments. Also, the sometimes difficult calibration procedure along with the drift sensitivity of these EMI sensors has stood in the way making them part of the archaeologist's survey toolbox. Nevertheless, EMI has the potential to provide detailed

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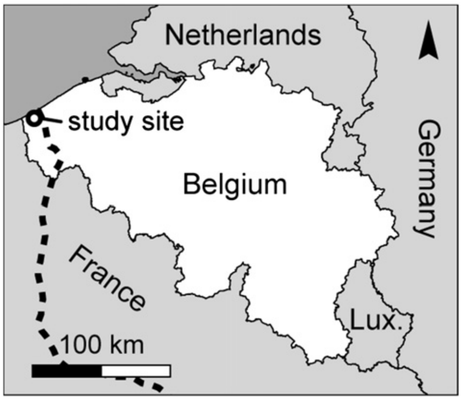

Fig. 1. Location of the study site near the North Sea coast and the French border. The World War I frontline is indicated by the dashed line.

maps of the subsurface and, in contrast to GPR and magnetometry, it can provide information on soil properties such as soil texture, organic matter content and water content. The recent introduction of multi-receiver EMI sensors (e.g. Geonics MK-2, Dualem-1S) has increased their potential as these instruments not only allow measuring the ECa of varying soil volumes, but also add simultaneous measurements of soil apparent magnetic susceptibility (MSa). These multi-receiver configurations add vertical discrimination potential to EMI survey (e.g. Saey et al., 2008) and have the ability to detect magnetic anomalies (e.g. Simpson et al., 2009). Moreover, the combination of ECa measurements allows accurately locating buried metal objects (Saey et al., 2011).

We used a mobile multi-coil EMI sensor for the archaeological prospection of a 90 ha polder site in Belgium prior to the development of a golf turf. Apart from the cost-time benefit of a mobile survey, the high groundwater level at the site and the possible presence of unexploded ammunition (UXOs) complicated the deployment of a full-scale trenching programme as a primary prospection method. The high clay content of the area, combined with the need to gather archaeological, geomorphological and pedological data, made EMI based proximal soil sensing an efficient way to guide further fieldwork. Our aim is therefore to demonstrate the potential of a multi-receiver EMI-survey in supporting and guiding geoarchaeological evaluations. In particular, a synthetic overview will be given of the range of vertical information that was obtained from simultaneous ECa measurements of different soil volumes.

2. Materials and methods

2.1. History and pedology of the study area

The 90 ha study area is situated in the municipality of Koksijde in the north-western part of Belgium (Fig. 1). Located within the coastal plain, 3 km south of the shoreline, the pedology of the site mainly consists of a clayey topsoil overlaying a former intertidal sand flat dissected by tidal channels. The Quaternary sediments have been deposited in a silting up process of tidal channels that are still present in the subsurface as palaeoriver systems filled in with sandy to heavy clay sediments and intercalated peat layers (Baeteman, 2008). Within the study area, occupations are attested from the late Carolingian period (9th–10th century AD) onwards (Lehouck et al. 2011). Since the later Middle Ages, the area was mainly used as farm land.

In later periods, a number of conflicts left their marks on the study area; during World War I (WWI) (1914–1918), for example, the area was situated just behind the front (Fig. 1). Intensive artillery fire during this conflict had a substantial impact on the area and until today UXOs can be found. Shortly after WWI, the terrain was levelled and reinstated as arable land until the plans were made to convert it into a golf terrain in 2009. Today, the soil of this area is characterized by an AC_1C_2 profile (Inceptisols), where the plough layer is the A-horizon (Ap) that overlies clayey and sandy C-horizons.

2.2. Multi-receiver EMI

In accordance with the pedological constraints (i.e. high clay content and often water saturated sediments, which excluded the use of GPR instruments) and the need to gather both landscape and archaeological information, multi-receiver EMI was chosen as one of the main prospection techniques. We used a mobile configuration of the Dualem-21S EMI sensor (Fig. 2). This instrument has four coil configurations, so it measures the ECa and MSa of four different soil volumes simultaneously. As the sensor has been calibrated during production, on-field calibration is no longer a requirement. Apart from one transmitter coil (T), it has four receiver coils (R) of which two are placed in a perpendicular (PRP) and two in a horizontal coplanar (HCP) orientation. The T-R distances are 1 m (1 HCP), 1.1 m (1.1 PRP), 2 m (2 HCP) and 2.1 m (2.1 PRP) (Fig. 3A). The quadrature-phase signal components, representative for soil ECa, from each coil pair have specific depth responses (McNeill, 1980; Wait, 1962) and their depth of investigation (DOI) is conventionally taken at 70% cumulative response. This results in the common assumption that these configurations have a DOI of 0.5 m (1.1 PRP), 1 m (2.1 PRP), 1.5 m (1 HCP) and 3.2 m (2 HCP) below the instrument (Fig. 3B) (Saey et al., 2009). The MSa component for each coil pair has a smaller depth response, with a maximum DOI of approximately 1.5 m below the sensor (Simpson et al., 2010).

By driving along parallel lines, 1.75 m apart, with one measurement cycle (four ECa and four MSa measurements) every 0.25 m, we obtained a quasi-complete coverage of the study area. At this resolution, targeting the main archaeological features ($\geq$1.5 m in diameter) and detailed geomorphological variations, it was possible to scan approximately 0.75 ha per hour.

2.3. Building a 90 ha EMI dataset

As the EMI measurements were performed during a period of 15 days, soil temperature variations caused additional variability.

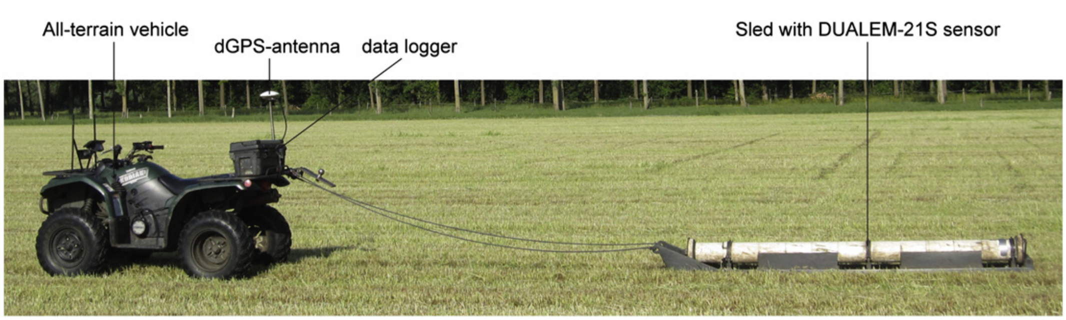

Fig. 2. The mobile survey configuration with the all-terrain vehicle towing the sled with the Dualem-21S sensor.

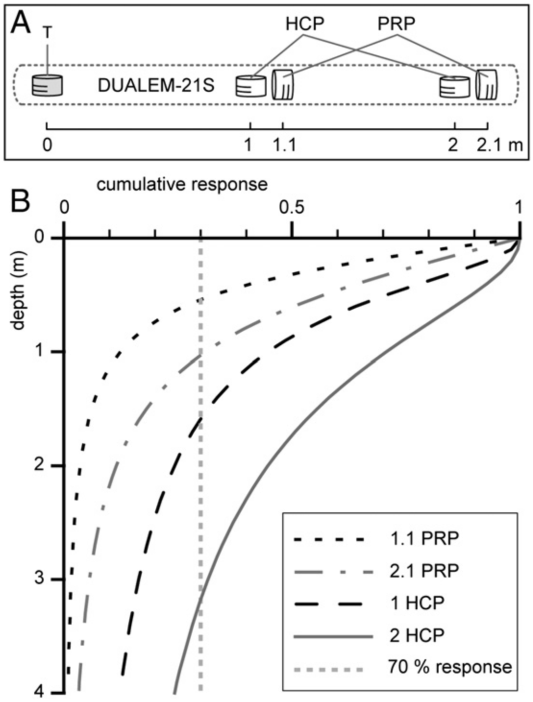

Fig. 3. Schematic representation of the Dualem-21S EMI sensor with indication of the transmitter (T) and the four receiver coils in both HCP and PRP dipole orientation (A) together with the depth response functions for the quadrature-phase signal component (ECa) of each coil pair (B).

Daily measurements of soil temperature at a soil depth of 30 cm, were used to convert the ECa measurements to a reference temperature of 25 °C (Saey et al. 2008; Slavich and Petterson, 1990). Potential temporal drift in the sensor data was corrected by including a calibration line, crossing the entire field prior to the actual survey (Simpson et al., 2009). Field data were then interpolated to a resolution of 0.5 m^2 using ordinary point kriging (Goovaerts, 1997) with Surfer (Golden Software, USA). Finally, all surfaces were combined into single raster images with ArcGIS 9.3 (ESRI, USA). While for the ECa data, more detailed analyses were performed to understand vertical variability, the MSa data shown in this paper were only used for interpreting lateral variations.

2.4. Looking into multi-layer ECa data

When multiple simultaneous ECa measurements from different coil configurations with distinct depth response functions are available, information about vertical facies changes can be gathered. Saey et al. (2009) showed that such data can be used to model the depth to clay in a two-layered soil, and more recently this methodology was applied to model the depth of palaeoriver-branches (De Smedt et al., 2011a). The modeling procedures in this study were based on the depth response functions for the DUALEM-21S coil pair ECa measurements in PRP (Wait, 1962) and in HCP mode when operating at low induction numbers (Callegary et al., 2007; McNeill, 1980). By combining these response functions, as in Eq. (1) (Saey et al., 2008, 2009), we modeled the depth of the sandy deposits (z_2), to reconstruct the palaeotopography of a part of the study area. Given the EC of each soil layer (EC_1, EC_2, EC_3), and by taking the sensor height (z_α) into account, the depth of a soil layer (respectively z_1 and z_2 in a three-layer soil model (Fig. 4A)) can be determined by incorporating the response (R) of each coil pair with orientation x and intercoil separation s:

$$\begin{aligned} ECa_{x,s} = & \left[R_{x,s}(z_1+z_\alpha) - R_{x,s}(z_\alpha)\right]\cdot EC_1 \\ & + \left[R_{x,s}(z_1+z_2) - R_{x,s}(z_1+z_\alpha)\right]\cdot EC_2 \\ & + \left[1 - R_{x,s}(z_1+z_\alpha)\right]\cdot EC_3 \end{aligned} \qquad (1)$$

To obtain EC_1, EC_2 and EC_3, 20 calibration augerings were performed to determine the interface depth of each soil layer. At these locations, the parameters EC_1, EC_2 and EC_3 were iteratively adjusted to get the smallest sum of the squared differences between the observed (z) and predicted (z^*) depths (De Smedt et al., 2011a). The resulting EC-values could then be used to model the depth of each soil layer through Eq. (1) at each measurement location (Fig. 4A). This system was solved in Matlab using the Levenberg–Marquardt algorithm (Marquardt, 1963). By subtracting the resulting predicted depths from available digital elevation data (DEM), the elevation of these different soil layers could be mapped.

To aid archaeological data interpretation, a second inverse method (EC-slicing) was developed based on Eq. (1), that allowed modeling the EC of predefined soil layers (Saey et al., 2012). This procedure was used to predict the EC of three predefined soil volumes (*Slice 1–3* in Fig. 4B). The resulting EC depth-slices could then be used to determine the depth of archaeological traces and to improve the visibility of targeted features.

Additionally the ‘fused electromagnetic metal prediction’ (FEMP (Saey et al., 2011)) was applied in some parts of the study area for metal detection. This method uses a filtering procedure applied to all four ECa measurements to focus on the local data anomalies. By converting the extreme values (e.g. outliers and local anomalies) to the mean value of neighboring measurements within a 10 m radius circular search window, a gradual trend originating from the natural soil variability was determined. Afterwards, this trend was removed

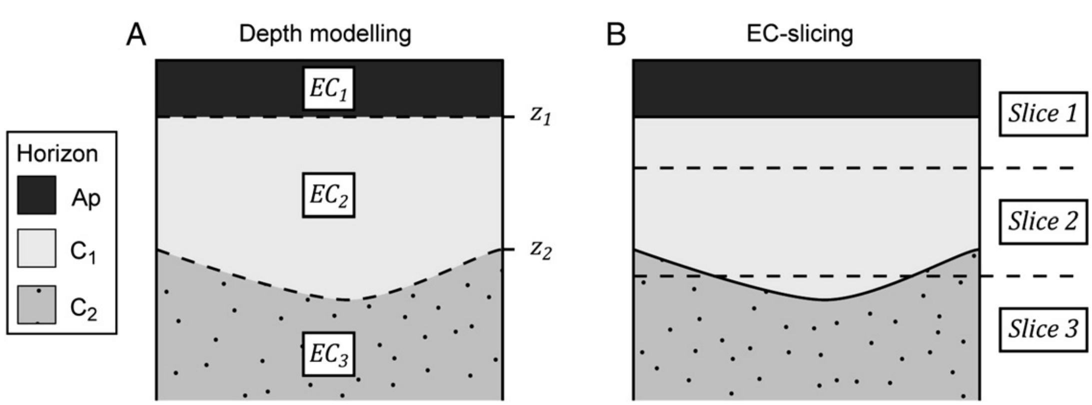

Fig. 4. Diagram of the two applied inversion procedures. In A the depth modeling procedure is show, aimed at finding the interface depths (z_1 and z_2) in a three-layered soil model by taking into account the electrical conductivities of each soil volume (EC_1, EC_2 and EC_3). B shows the aim of the EC-slicing procedure, which tries to reconstruct the EC of three predefined soil layers (Slice 1–3).

from the original ECa data to highlight the local anomalies. Finally, the residual ECa values from each coil configuration were combined and multiplied by weighting coefficients per coil pair to amplify the contrast between metal objects and the background. Further information about this procedure can be found in Saey et al. (2011).

2.5. Archaeological excavation

Based on the EMI data and other archaeological surveying, approximately 4 ha were excavated in detail by archaeologists (Lehouck et al. 2011). The depth of these excavations generally coincided with the depth to the sandy C-horizon in these areas. All archaeological and pedological features in the excavated areas were precisely drawn, digitized and georeferenced.

3. Results and discussion

The ECa measurements revealed a large variety of traces and patterns, both of natural and anthropogenic origin (Fig. 5). The fine resolution and continuous nature of the dataset, allowed tracing the lateral extent of many continuous features such as a palaeoriver system and the network of linear man-made ditch systems. In this study, three sites were selected based on the EMI data to analyze the variety of information that can be obtained with multi-receiver EMI survey (Fig. 5A).

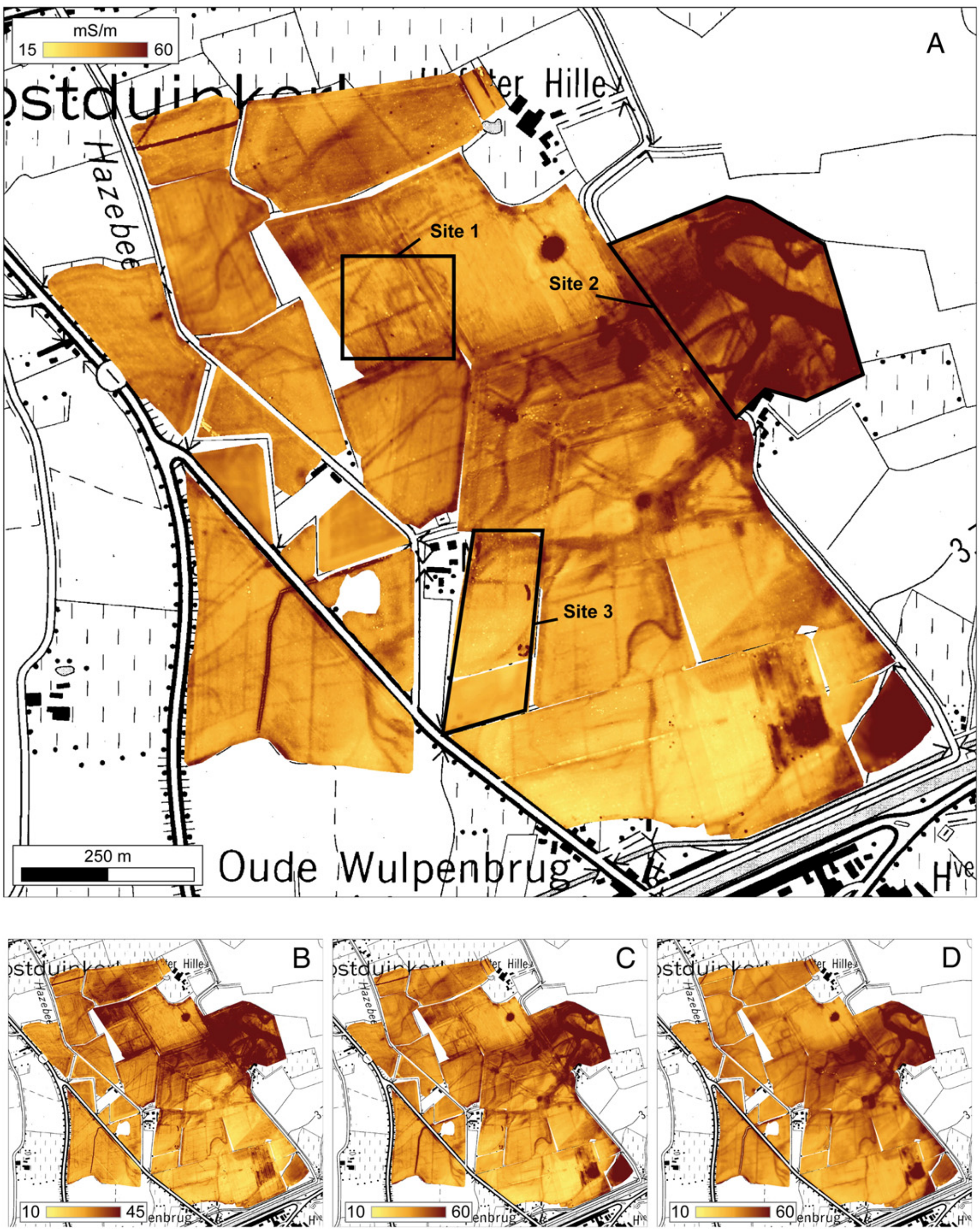

Fig. 5. Plot of the ECa data from the 1 HCP (A), 1.1 PRP (B), 2.1 PRP (C) and 2 HCP (D) coil configurations of the entire study area.

On sites 1 and 3 large archaeological features were found, whereas on site 2 a part of a large palaeoriver-system was detected. Both sites 1 and 3 were part of the archaeological excavation campaign.

3.1. Site 1: ECa depth slicing

By modeling the EC of three non-overlapping soil layers, i.e. 0–0.5 m (*Slice 1*), 0.5–1.0 m (*Slice 2*) and > 1.0 m (*Slice 3*) beneath the soil surface (Fig. 6), some features could be better discriminated and their vertical extent could be accounted for (Saey et al., 2012). While there was little EC variability in the topsoil (Fig. 6B), *Slice 2* demonstrated a large conductivity contrast between archaeological and pedological phenomena (Fig. 6C). In addition, this contrast was enhanced by exclusion of the topsoil noise and rubble in *Slice 1*, which allowed a better delineation of the archaeological features in *Slice 2*. The EC of the soil below 1 m (*Slice 3*, Fig. 6B) showed that, although most features could no longer be seen, a number of structures extend below this depth. Furthermore, the decreasing EC values in these deeper soil layers indicated a more resistive soil material, corresponding to the underlying sand. In this deepest soil volume, however, there do appear a number of artefacts, as traces of the deepest conductive features (e.g. the parcel ditch) sometimes appear as areas with higher resistivity.

When the EC of the *Slice 2* was compared to the available excavation results, all of the large archaeological features could be clearly discriminated in the modeled EC plot (Fig. 6C). Of these features, the smallest verified anomaly had a width of 1.5 m. These excavation data also confirmed the vertical extent of the discerned features between 0.5 and 1 m beneath the soil surface. Compared to the original ECa measurements (Fig. 6A), the modeled data allow a straightforward distinction of the main archaeological structures as the topsoil anomalies have been removed, along with the deeper pedological variation isolated in *Slice 3*. For instance, together with the medieval farmstead moat, the farmyard ditch can now be distinguished better as the clayey topsoil masked the full extent of the farmyard ditch in the unprocessed ECa measurements.

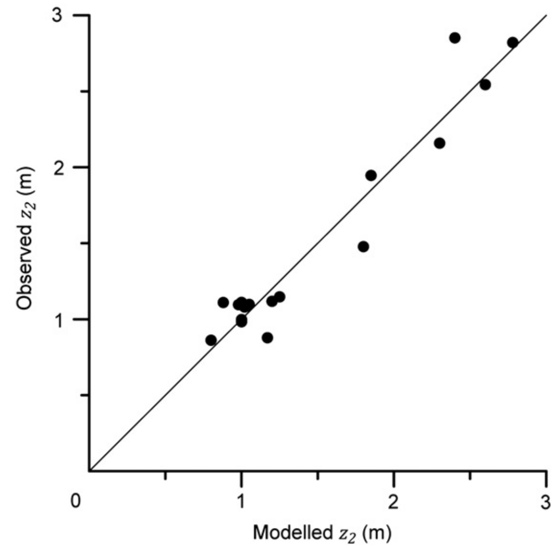

Fig. 7. Scatter plot comparing the observed and modeled depths to the sandy C-horizon underlying the palaeochannel deposits (z_2).

3.2. Site 2: palaeotopographical modeling

Based on the calibration data from 20 locations (Fig. 8A), parameters EC_2 and EC_3 were found to be 109 mS m^{-1} and 9 mS m^{-1} and were assumed to be uniform across site 2. Because of topsoil heterogeneity, EC_1 could not be generalized for this area. Instead, z_1 was set to 0.3 m based on the same calibration augerings. With this assumption

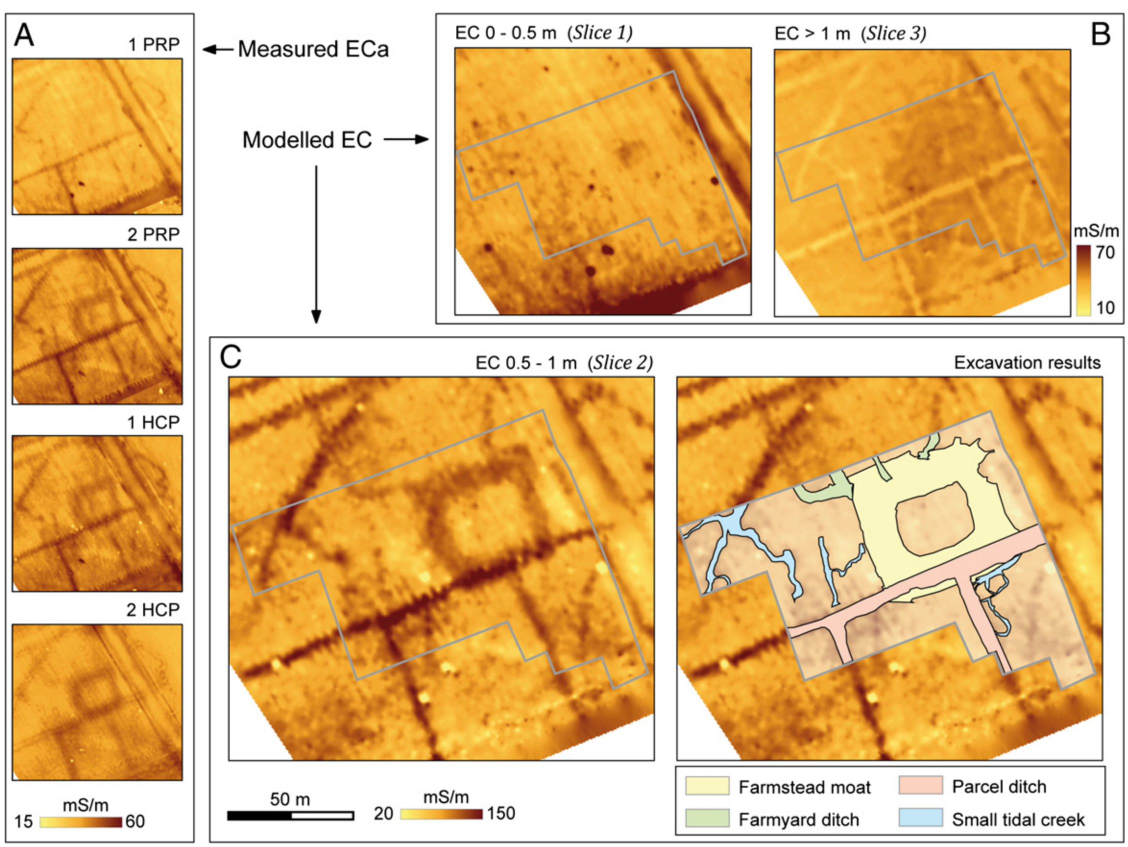

Fig. 6. Dualem ECa measurements from site 1 (A), with modeled EC for topsoil (Slice 1) and substrate (Slice 3) soil volumes (B) and the modeled EC of the soil volume between 0.5 and 1 m (Slice 2) below the sensor with and without excavation results (C).

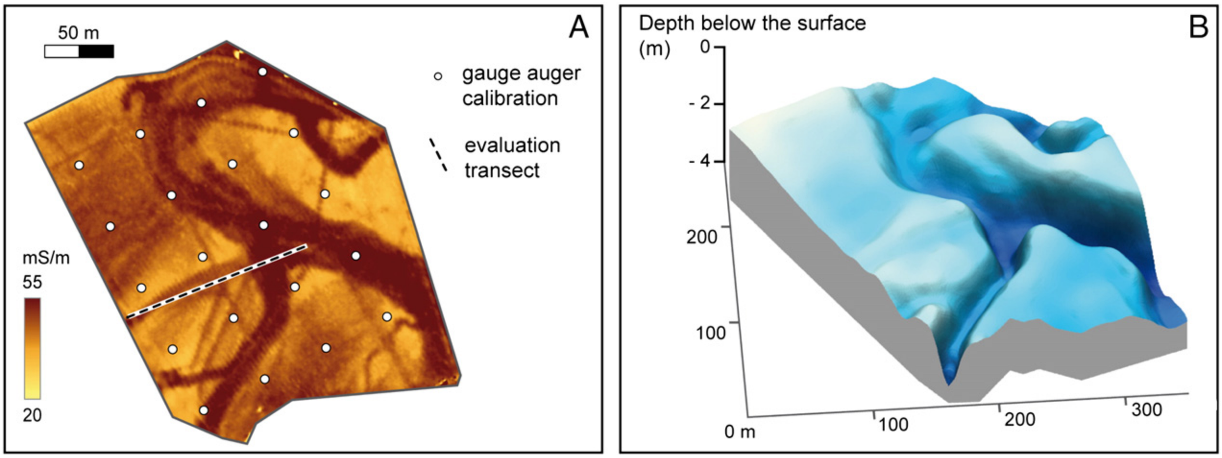

Fig. 8. 1 HCP ECa data from site 2 with calibration and evaluation sampling locations (A) with the depth model from the site (B).

z_2 could be predicted through Eq. (1) by using the ECa data from the four coil configurations. The resulting palaeochannel depths ranged from 0.41 m to 4.89 m beneath the surface. These were verified at 16 locations along transect AB (Figs. 7 and 8A). At these locations, the Pearson correlation coefficient between the predicted and actual depths was 0.91, while the MEE and RMSEE were 0.11 m and 0.23 m, respectively, which are acceptable results.

After subtracting the z_2^* values from the DEM, the palaeotopography and the morphology of the palaeoriver segment could be plotted three-dimensionally (Fig. 8B). This geomorphological model can support detailed landscape reconstructions and, combined with the archaeological data, forms a framework for understanding settlement history of the area. Hypotheses about the potential threat of floodings and the capacity for navigating small vessels through this palaeoriver can now be tested by modeling stream flow and river discharge.

3.3. Site 3: MSa, metal detection and battlefield archaeology

Apart from the variations recorded in the ECa datasets, the MSa measurements of the study area also revealed archaeological remains. At site 3, four WWI structures were detected (Fig. 9). Based on the typology of these features, they have been identified as fire trenches of the Belgian army with square traverses. Furthermore, through comparative aerial photographic research it was possible to date these features between September 4, 1917 and April 12, 1918. The trenches at the Koksijde site consisted of large breastworks (up to 13 m wide) that were constructed above the surface. Most of the anomalies detected on the MSa measurements (Fig. 9, anomalies a–d) are in fact the “negative traces of the fire trenches”, namely the borrow pits from where the soil was removed to build the above surface breastwork.

A fifth anomaly found on the MSa measurements could be linked to a pile of mixed material, also visible on the aerial photographs

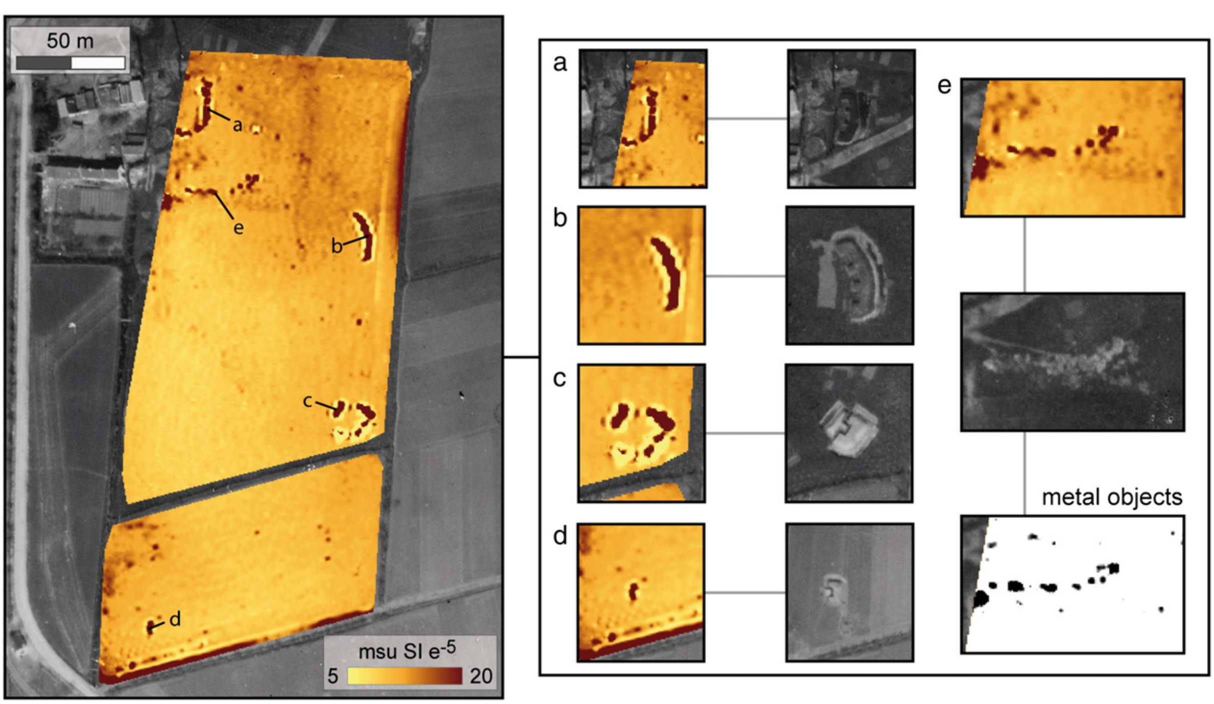

Fig. 9. MSa data from the 2 HCP coil configuration plotted on top of a georectified WWI aerial photograph dated to April 1918 (Source: Belgian Royal Army Museum, Photos Aériennes '14–'18). Details on the right show four of Belgian fire trenches visible in the MSa data (a–d), detail e shows a pile of unidentified material related to military activities at the site. At the bottom results of the FEMP-analysis show the metal objects as black dots scattered over the feature.

(Fig. 9 anomaly e). While some of these features were also visible on the ECa datasets, this fifth anomaly could only be clearly identified and isolated on the MSa maps. By then applying the FEMP-procedure for metal detection to the ECa data of the site, it was possible to identify the presence of metal objects in this feature (Fig. 9 e).

4. Perspectives and conclusion

Although the application of EMI sensors in archaeology is still limited when compared to the use of other geophysical techniques, these case studies clearly show their potential in geoarchaeological site evaluation. Using a mobile configuration of a multi-receiver EMI instrument adds both lateral and vertical discrimination potential in a time efficient and non-destructive manner. Fine-tuning of the method allows detecting smaller features and the different penetration depths of the coil pairs enable reconstructing ECa depth variations and offer the possibility to extend this vertical analysis to MSa variability. However, as the applied measurement resolution in this study focuses on the larger archaeological traces, the potential of this methodology in discerning smaller archaeological anomalies such as pits and postholes, as well as the added value of multiple MSa measurements, will be further investigated (De Clercq et al., 2012, De Smedt et al. 2011b). Furthermore, the efficient simultaneous implementation of different geophysical techniques needs to be taken on.

Of particular importance for geoarchaeological evaluation is the possibility to simultaneously gather detailed information about the landscape and the archaeology it contains. The data layers recorded with a multi-receiver EMI survey allow mapping the palaeotopography and pedological variation as well as detecting archaeological features and metal objects. Especially the integration of simultaneously recorded MSa data can be a valuable asset to help discerning between pedological and anthropogenic soil features. Combined with additional data, such as aerial photographs and digital elevation models, the interpretation of these geophysical data can be facilitated and improved.

Nevertheless, the need for data verification due to the complex and heterogeneous nature of archaeological features and contexts, remains crucial. Therefore, the incorporation of processed sensor data in archaeological surveys should be alongside augering and trenching. The challenge lies in the design and implementation of efficient, integrated survey strategies. Here, it can be concluded that multi-receiver EMI instruments, together with other proximal soil sensing techniques and complementary inverse modeling procedures, are becoming an indispensable part of geoarchaeological investigation.

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