IMEKO International Conference on
Metrology for Archaeology and Cultural Heritage
Lecce, Italy, October 23-25, 2017

Multi-frequency EMI in archaeological prospection: case studies of Han Hangu Pass and Xishan Yang in China

Panpan Tang[1], Fulong Chen[1*,] Aihui Jiang[1] a,b, Wei Zhou[1] a,b, Hongchao Wang[2]c, Xin Lu[2]c , Giovanni Leucci[3], Lara de Giorgi[3], Maria Sileo[3], Lupeng Luod[4] , Nicola Masini[3]

[1] Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, No. 9 Dengzhuang South Road, Haidian District, Beijing 100094, China; E-Mails: tangpp@radi.ac.cn
[1] International Centre on Space Technologies for Natural and Cultural Heritage under the Auspices of UNESCO, No. 9 Dengzhuang South Road, Haidian District, Beijing 100094, China;
[2] Institute of Conservation and Management of Xin'an Hangu Pass (Han Dynasty), Cultural Relic Bureau of Xin'an County, Luoyang, 471800, China.
[3] Institute for Archaeological and Monumental Heritage, National (Italian) Research Council (CNR), Prov.le Lecce-Monteroni, - 73100 Lecce; C/da Santa Loja s.n.c., 85050 Tito Scalo (Potenza), Italy.
[4] Institute of Cultural Relics and Archaeology of Zhejiang Province, Hangzhou, 310014, China

Abstract – Among geophysical techniques applied to archaeological sites , the multi-frequency EMI method is capable of identifying shallow subsurface relics by simultaneously measuring the apparent electrical conductivity (ECa) and apparent magnetic susceptibility (MSa).In this study, multi-frequency EMI technologies were performed in two heritage sites with different geological conditions. In the site of Han Hangu Pass, high ECa values were measured due to the cinnamon soil. Variations of ECa from the surface to shallow subsurface with different depths indicate a correlation with archaeological excavations. Whereas, electromagnetic anomalies related to an ancient road and five kiln caves were identified. In the Xishan Yang, sandy loams result into lower ECa values. An ancient tomb, indicating extremely low ECa and high MSa, was discovered. Its electromagnetic properties is attributed to the cavity and ferroferric oxides. Afterwards, the depths of investigation (DOI) in conjunction with the performance of signal frequencies were assessed and analyzed.

I. INTRODUCTION

For the archeological prospection the traditional field methods, such as extensive trenching, hand augering and popular Luoyang Spade in China, have been proved effective in the early stage of archaeological evaluation (1). Prior to excavation the Archaeological prospection are an essential step in assessing the conservation value of heritage buried (2). However, the traditional methods are time/cost-consuming, invasive as well as constrained by complex geological conditions. for these reasons the geophysical techniques have been adopted in archeology since sixty years ago (3, 4), including the methods of electrical (5), magnetic (6,7), electromagnetic (8,9;), microgravity (10) and ground penetrating radar (GPR) (11, 12), also in the context of remote sensing based investigations (13, 14). They have increasingly played an essential role and opened new perspectives (14 in archaeological field excavation owing to the improvements of sampling instruments and processing softwares (15).

Electromagnetic induction (EMI) measures the apparent electrical conductivity (ECa) and apparent magnetic susceptibility (MSa) simultaneously. The survey is usually operated with high-efficient, cost-beneficial and non-invasive. Though EMI method has been studied by archeologists (16,9, 17), its extended applications in archaeology remain inadequate due to certain causes mentioned by De Smedt et al.(2). The introduction of multi-coil or multi-frequency EMI sensors has recent increased the ability of determining vertical structures by obtaining signatures at different depths of investigation (DOI) (18).

In this study, multi-frequency EMI method was applied for archaeological prospection in two heritage sites in China. The first is ancient Han Hangu Pass in Luoyang City that used to be an important military fort in the Western Han dynasty, 114 BC. It was included into the cluster of Silk Roads sites: the Routes Network of Chang'an-Tianshan Corridor that was inscribed on the UNESCO World Heritage List in 2014. It was played as the first eastern gateway of the land "Silk Road". The second study site is Xishan Yang, a famous national wetland park in Zhejiang province. Ancient tombs with various scales dated back to several centuries are widely distributed among the hills of the site.

In this study, results and interpretations of EMI surveys in conjunction with quantitative analyses were reported. We aims to demonstrate the potential of multi-frequency EMI survey in archaeological prospection for future investigations.

II. STUDY AREA

Locations of two study sites were shown in Fig.1a. The Han Hangu Pass is located in a valley of Xin'an county, Luoyang city. Hills stand on both the north and south sides with the elevation up to 100 m. A river, railway and highway go through the site along the East-West (E-W) direction. (Fig.1b).

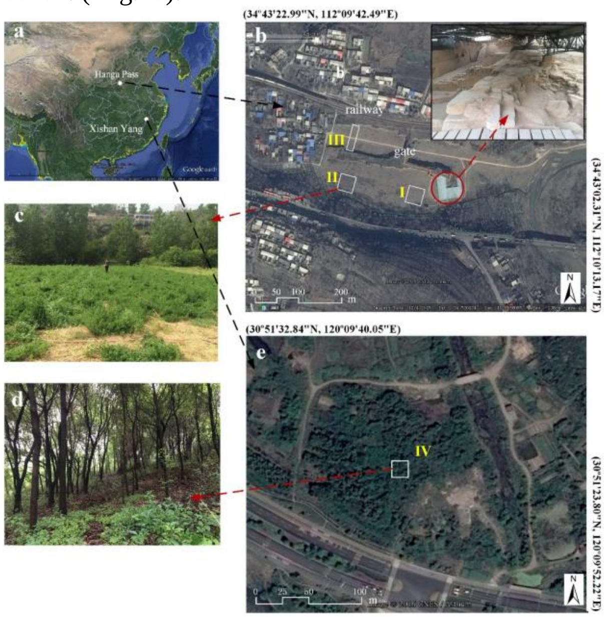

Fig. 1. (a) Locations of two study sites. (b) Google earth map of Hangu Pass. (c) Photo of region II. (d) Photo of region IV. (e) Google earth map of Xishan Yang.

Existing monuments on the surface mainly include a pass gate, inner walls and two ancient structure foundations named Jiming and Wangqi. The conducted excavation and drilling (period of 2012-2013), brought to light plentiful of cultural relics, Fig.1b . The subsoil are comprised of three layers from surface to deep, the depth of two upper layers are approximately 2 m totally. Then the EMI surveys were performed in three regions (I, II and III), with the areas of 40×25, 36×30 and 50×15 sq.m., respectively. Region I and II are covered by dense vegetation (see Fig.1c).

Xishan Yang is a wetland park under construction in Huzhou city, Zhejiang province. Due to its location that closes to the Tai Lake and the Yangtze River, ancient residents made up tombs at a relatively higher altitudes among hills, but relics of ancient tombs are still not discovered today. A study region IV with an area of 12×25 sq.m was selected in a hill covered by dense trees (see Fig.1d and 1e). The soil in the hill is mainly composed by sandy loam.

III. METHOD AND DATA COLLECTION

EMI sensors transmit 'primary' electromagnetic (EM) field and receive the 'secondary' EM field through inducing the alternating currents in the soil (19,20). Generally, EMI sensors could be classified into frequency-domain (FD) and time-domain (TD) categories. FD sensors are used to derive the ECa and MSa, working both as a magnetometer and a conductivity meter (21, 22). ECa and MSa can be used to define the conductivity and susceptibility of a homogeneous half-space that would generate the same response as surveyed over the real earth.

ECa mainly depends on the combination of soil physico-chemical properties of clay content and mineralogy, soluble salts, soil content, compaction, and etc (23). It is proportional to the moisture held by the soil particles as well as is positively correlated with the soil compaction. According to Grisso et al. (24), the clay is more conductive than the silt, and the sandy soil is most resistive. MSa is related with the type, content and particle size of magnetic minerals, which generally can be classified into ferromagnetism, paramagnetism and diamagnetism. Ferromagnetism materials have the large susceptibility, e.g. iron. Paramagnetism materials mainly include the transition and rare earth metals, as well as gas of the oxygen, indicating small positive susceptibility values. The susceptibilities of diamagnetism corresponds to common materials comprised by copper, silver, gold, zinc, graphite, inactive gas and most organic matters

In this study, a hand-held, digital and multi-frequency broadband electromagnetic (so-called Geophex GEM-2) was used. This instrument is able to transmit and receive any digitally synthesized waveform by means of the technology of pulse-width modulation. It is portable with a light weight, allowing a surveyor to cover approximately one acre per hour with up to ten frequencies ranging from 30 Hz to 93 KHz. However, it is not necessary to acquire signatures with more than 4-5 frequencies because no more information would be obtained due to the performance limitation of sensors. It is bistatic with a transmitter coil and a receiver coil separated by 1.6 m. Two calibration sets (amplitude and free-air calibration) had been done at the Geophex factory. The maximum DOI can research deep to 20-30 m in resistive regions (> 1000 ohm-m) and 10-20 m in conductive regions (< 100 ohm-m) (Huang, 2005).

Five wave frequencies, ranging from 525Hz to 57075Hz, were used for the surveys. The sampling intervals are 0.5 m (region I and II), 1 m (region III) and 0.3 m (region IV and V), respectively. The GEM-2 sensor has three filters for smoothing noise and improving result maps. In this study, the median filter using a moving window was selected. The three-layer model was adopted for the depth inversion. The point data collected were interpolated into 2D or 3D maps by the method of Craig grid. The unit of conductivity is milli-siemens per meter (ms/m) and the susceptibility is dimensionless. To enhance the visualization effect, ECa values were logarithm-stretched and all MSa values were amplified by a factor of one thousand.

IV. RESULTS AND DISCUSSIONS

n this study, 2D maps of ECa and MSa at different frequencies, and 3D maps of resistivity along depth with individual slices were used to highlight the subsurface features. Electric or magnetic anomalies were detected in the surveying regions though the signature in Region I and II was seriously affected by a buried electric piping with strong electromagnetic field. Several anomalies are caused by modern human activities while the others obtain responses from ancient relics. Data of past archaeological excavations were applied to analyze, interpret and validate EMI results.

The expected penetration depth, constrained by the soil conductivity and frequency, can be calculated by the 'Skin Depth Nomogram' (25). By using the median values of conductivities from the GEM-2 sensors, the expected depth of the five frequencies in two sites are approximately 1~10 m and 3~15 m with the maximum estimated DOI of 10 m and 4 m, respectively. Much deeper information were acquired in the site of Han Hangu Pass, whose estimated DOI approximately equals to the skin depth; while in the Xishan Yang site, the corresponding value is much smaller, that is approximately one ten of the skin depth. This phenomenon can be interpreted by the complex geological condition of the second site.

In this study, the maps of 525Hz and 1075 Hz in the Han Hangu Pass, and 925Hz in Xishan Yang, were much noisier than the other frequencies, resulting in confused information on the bottom layer of 3D resistivity maps.

In the Han Hangu Pass, the geophysical results were significantly interfered by the past archaeological excavations and infrastructure (e.g. the piping line) construction. In general, the measured ECa values increase gradually with the depth in the near-surface in conjunction with the rapid decline of values in deeper layers. This phenomenon results in the occurrence of the maximum values in the middle layer, corresponding to the interface between back-filled soil and raw soil. In contrast, the maximum absolute values of MSa occurs in the shallowest layer that could be related to the modern and/or past human activities. The surveying region in Xishan Yang is covered by natural surfaces. The maximum ECa values were observed in the deep layers interpreted by the increase of soil moisture with the increasing depth. And for the measurement of MSa in the Xishan Yang, the hypothesis became not true. The ECa values measured in the Xishan Yang were much smaller than that in the Han Hangu Pass, validated by the median values of approximately 1.8 ms/m and 8.6 ms/m, respectively. This can be contributed by the difference of soil properties, e.g. loess or cinnamon soil in the Han Hangu Pass versus sandy loam in latter site.

Region I

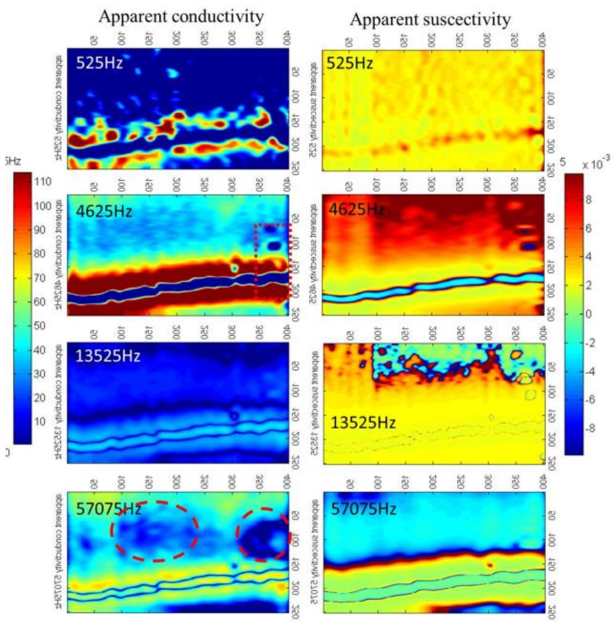

Fig.2. ECa maps (a, c, e) and MSa maps (b, d, f) of Region I at the frequencies of 525 Hz, 4625 Hz 13525Hz and 57075Hz.

Figure 2 shows the maps of EC_a and MS_a of region I at the frequencies of 525Hz, 4625Hz, 13525Hz, 57075Hz. Extreme values with a linear shape were observed caused by a buried electric piping. Three electric anomalies with conductivity lows, indicated as dash dot were detected. These three anomalies are generally legible on the high-frequency EC_a maps, and then tend to be obscure and even totally disappear at the low frequencies, implying the occurrence of targets in a shallow layer. Considering that this region had experienced past archaeological excavations, conductivity lows can be related to the loose back-filled sediments compared with the conductive compacted medium surroundings.

Region II

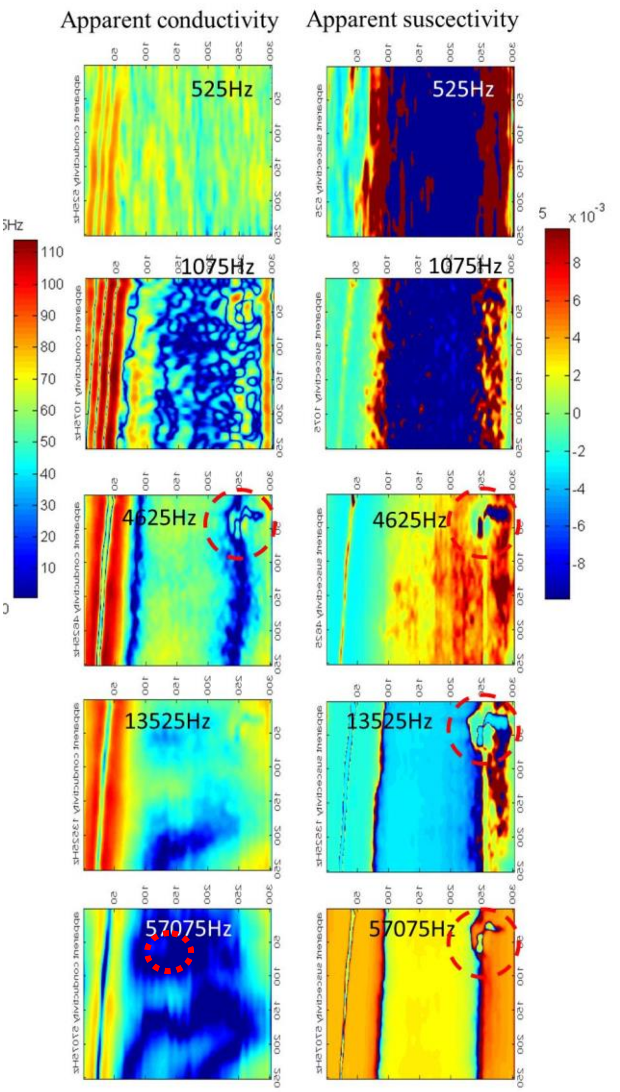

Fig.3. ECa maps (a, c) and MSa maps (b, d) of region II at the frequencies of 57075Hz and 13525Hz

Region II has the same geological conditions compared with Region I, validated by the analogous characteristics of ECa and MSa in different depth layers. Figure3 shows the results of five frequencies. Dashed dot areas refer to the elongated anomalies of conductivity lows (see Fig.3), responding to two digging areas. Magnetic anomaly (see Fig3) was found at various depths of different frequencies. It is located outside of the digging areas and was not detected in past excavations. High MSa values are probably related to the ancient artifacts, such as the construction materials of bricks and tiles (excavated in the past archaeological surveys).

Region III

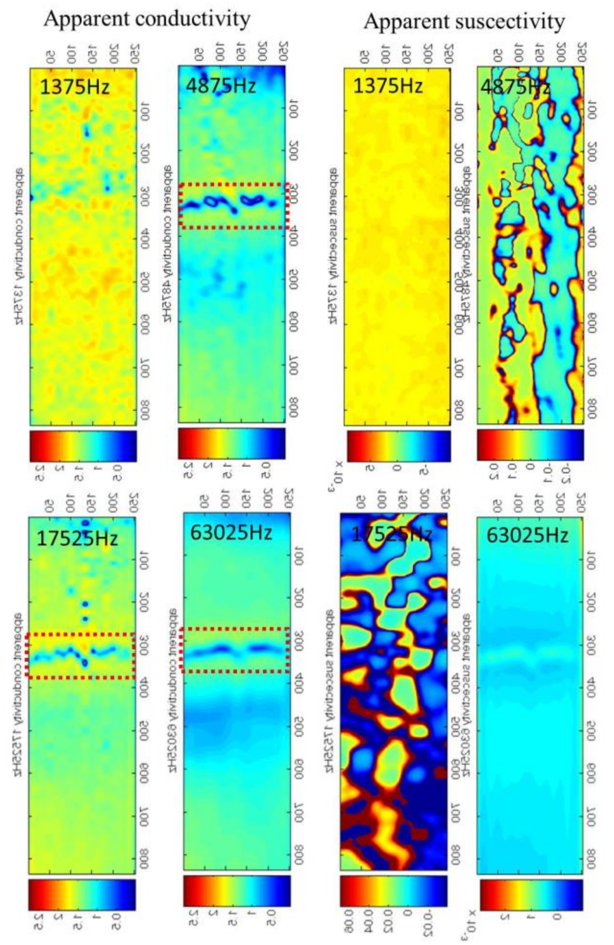

Fig.4. *EC_a map and MSa maps of region III at the frequency of 57075Hz*

The EMI survey was performed in this region because several ancient roads has been documented and even identified by the past archaeological excavations. Fig.4 shows the digging scene of an E-W stretching ancient road around 6 m away from the region we investigated. Its buried depth is approximately 4m with a width of 4.5-6m. Fig.5 shows the digging scene of an E-W stretching ancient road around 6 m away from the region we investigated. Its buried depth is approximately 4m with a width of 4.5-6m. The road soil, composed of sandy loam, is light brown and compressively stiff. In region III, a suspected ancient road regarding to the western section of the one identified in the past excavation, was detected in the EMI results. The anomaly appears on both the ECa maps of high frequencies (see Fig.4). Lower values are associated with the medium of sandy soil, which is much more resistive than its surrounding cinnamon soil.

Fig.5. An ancient road found in the past archaeological excavation.

V. CONCLUSION

EMI surveys using a multi-frequency sensor (GEM-2) was performed in two archaeological sites. ECa and MSa values were acquired simultaneously at five frequencies ranging from 525Hz to 57075Hz. Results demonstrate that extremely low frequencies (such as lower than 2000Hz) generally indicates low voltage, low signal-to-noise ratio and low resolution, and thus are not recommended. 3D resistivity-depth maps were generated with the three-layer soil model. They are useful to quantify the buried depths and vertical properties of features, although the resistivity tends to be slightly underestimated as well as the overestimation of the DOI. Besides the imprints of archaeological excavations, ancient relics including the suspected kiln caves, a road and a tomb were detected. Case studies reported indicate the potential of multi-frequencies EMI technologies in archaeological prospection, particularly considering the advantages of non-invasive, high-efficient and low-cost. it is essential to consider the geological condition and physicochemical properties of relics in geophysical campaigns. Parameter optimization of sensors could be another issue, such as the selection of proper frequencies, sampling direction, interval as well as the inversion algorithms. Finally, the collaboration between differential professionals and the interdisciplinary interpretation using space technology, geophysics, environment and archaeology could be a promising solution in future archaeometry.

REFERENCES

[1] De Clercq, W., Bats, M., Laloo, P., Sergant, J., Crombé, P., 2011. Beware of the known. Methodological issues in the detection of low density rural occupation in large surface archaeological landscape-assessment in Northern-Flanders (Belgium). In: Blanquaert, G., Malain, F., Stäube, H., Vanmoerkerke, J. (Eds.), Understanding the past: a matter of surface-area. Acts of the XIIIth session of the EAA congress, Zadar. British Archaeological Reports, International Series. Archaeopress, Oxford, pp. 73–89.

[2] De Smedt, P., Saey, T., Lehouck, A., Stichelbaut, B., Meerschman, E., Islam, M.M., De Vijver E.V., Meirvenne, M.V., 2013. Exploring the potential of multi-receiver EMI survey for geoarchaeological prospection: a 90 ha dataset. Geoderma 199 (2), 30–36.

[3] Atkinson, R.J.C., 1952. Méthodes électriques de prospection en archeologie, in: Laming, A. (Ed.), La découverte de passé. Picard, Paris, pp. 59–70.

[4] Aitken, M.J., 1974. Physics and Archaeology, second ed. Clarendon Press, Oxford, pp. 286.

[5] Hesse, A., 2000. Count Robert du Mesnil du Buisson (1895-1986), a French precursor in geophysical survey for archaeology. Archaeol. Prospect. 7 (7), 43–49.

[6] Belshé, J.C., 1957. Recent magnetic investigations at Cambridge University. Adv. Phys. 6 (22), 192–193.

[7] Aitken, M.J., Webster, G., Rees, A., 1958. Magnetic prospecting. Antiquity 32, 270–271.

[8] Zheng, W.F., Li, X.L., Lam, N., Wang, X.B., Liu, S., Yu, X.Y., Sun, Z.L., Yao, J.M., 2013. Applications of integrated geophysical method in archaeological surveys of the ancient Shu ruins. J. Archaeol. Sci. 40 (40), 166–175

[9] Gao, X., Cote, P., Blais, J.P., Dong, W., Tong, H.W., Derobert, X., Palma Lopes, S., Zhang, S.Q., Chen, F.Y., 2016. Geophysical investigations identify hidden deposits with great potential for discovering Peking Man fossils at Zhoukoudian, China. Quatern. Int. 400, 30–35.

[10] Linford N., 2004. From Hypocaust to Hyperbola: Ground-penetrating Radar Surveys over mainly Roman Remains in the UK. Archaeol. Prospect. 11 (11), 237–246.

[11] Masini N., Capozzoli L., Chen P., Chen F., Romano G.,Lu P., Tang P., Sileo M., Ge Q., Lasaponara R., 2017. Towards an operational use of geophysics for Archaeology in Henan (China): Archaeogeophysical investigations, approach and results in Kaifeng. ***Remote Sensing*** 9 (8), 809, doi: 10.3390/rs9080809.

[12] Lasaponara R., Leucci G., Masini N., Persico R., Scardozzi G., Towards an operative use of remote sensing for exploring the past using satellite data: The case study of Hierapolis (Turkey), Remote sensing of Environment, 174 (2016) : 148–164, doi:10.1016/j.rse.2015.12.016

[13]F. Chen, N. Masini, Jie Liu, Jiangbin You & R. Lasaponara (2016): Multi-frequency satellite radar imaging of cultural heritage: the case studies of the Yumen Frontier Pass and Niya ruins in the Western

Regions of the Silk Road Corridor, International Journal of Digital Earth, 9 (12), 1224-1241; doi: 10.1080/17538947.2016.1181213

[14] Kvamme, K.L., 2003. Geophysical surveys as landscape archaeology. American Antiquity 68 (3), 435–457.

[15] Novo A., Vincent, M.L., Levy, T.E., 2012. Geophysical Surveys at Khirbat Faynan, an Ancient Mound Site in Southern Jordan. Int. J. Geophys. 2012.

[16] Conyers, L.B., Ernenwein, E.G., Grealy, M., Lowe, K.M., 2008. Electromagnetic conductivity mapping for site prediction in meandering river floodplains. Archaeol. Prospect. 15 (2), 81–91.

[17] Simpson, D., Lehouck, A., Verdonck, L., Vermeersch, H., Van Meirvenne, M., Bourgeois, J., Thoen, E., Docter, R., 2009. Comparison between electromagnetic induction and fluxgate gradiometer measurements on the buried remains of a 17th century castle. J. Appl. Geophys. 68 (2), 294–300.

[18] Saey, T., De Smedt, P., Meerschman, E., Islam, M.M., Meeuws, F., Van De Vijver, E., Lehouck, A., Van Meirvenne, M., 2012. Electrical conductivity depth modelling with a multireceiver EMI sensor for prospecting archaeological features. Archaeol. Prospect. 19 (1), 21–30.

[19] Doolittle J.A., Brevik, E.C., 2014. The use of electromagnetic induction techniques in soils studies. Geoderma 223 (s 223-225), 33–45.

[20] Calamita, G., Perrone, A., Brocca, L., Onorati, B., Manfreda, S., 2015. Field test of a multi-frequency electromagnetic induction sensor for soil moisture monitoring in southern Italy test sites. J. Hydrol. 529 (1), 316–329Won et al., 1996

[21] Won, I.J., Keiswetter, D., Fields, G., and Sutton, L., 1996, GEM-2: A new multifrequency electromagnetic sensor: J. Environ. Eng. Geophys. 1 (2), 129–137.

[22] Won, I.J., Keiswetter, D., Hanson, D., Novikova, E., and Hall, T., 1997, GEM-3: A monostatic broadband electromagnetic induction sensor: J. Environ. Eng. Geophys. 2 (1), 53–64.

[23] Al-Gaadi, K., 2012. Employing electromagnetic induction techniques for the assessment of soil compaction. Am. J. Agric. Biol. Sci. 4, 425–434.

[24] Grisso, R., Alley, M.M., Holshouser, D., Thomason, W., 2009. Precision farming tools: Soil electrical conductivity. Virginia Polytechnic Institute and State University, Virginia State.

[25] Won I.J., 1980. A wideband electromagnetic exploration method – Some theoretical and experimental results, Geophysics 45 (5), 928–940.