The role of EMI in development planning: the case of the Grands Philambins enigma

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Abstract

Spatial planning aims at constantly improving the distribution of people and activities within available space, especially near cities on ancient agricultural or industrial areas. However, a proper schedule of the development work necessitates to assess as precisely as possible the difficulties that would be encountered in terms of geotechnical abilities of the terrain and hazards resulting from previous use. In the Grands Philambins site three different geophysical techniques were combined, multi-depths resistivity, magnetic gradiometry and electromagnetic induction (EMI). The aim of this study was to map, in a few days and with high measurement densities, all the EM properties of the terrain and to evidence metallic features. The acquired data were compared with prior documentation, mainly the air photos acquired since the middle of the 20th century. The terrain structure is complex, at the junction of geological formations composed of limestones and marls in different proportions, which were characterised by the geophysical survey. It exhibits also metallic features, among which an enigmatic 70 m diameter radially striped disc object which was identified as non-ferrous and corresponding to an ancient antenna earthed socket. This case study illustrates the relevance of the use of EMI measurements in land planning studies as this method can map three independent underground properties and identify metallic features.

23

24 Key words

25 Development planning, EMI, electrical resistivity, magnetic susceptibility, permittivity, aerial photo,
26 archaeology, site characterization, metallic remains, site characterization.

27 Introduction

28 New development studies such as the construction of new buildings for housing, industry or
29 commercial areas, implies the coordination of a great number of actors and a precise schedule.
30 The miscalculation of the duration of a task can heavily disturb this schedule due to the lack
31 of availability of these actors: a prolongation of a few days for one task can delay the entire
32 project by several month. It is paramount for these projects to estimate as accurately as
33 possible the amount of work needed for each task. During the early stages of a construction,
34 the actors interact mainly with the soil and its substrate. Therefore, an accurate knowledge of
35 the soil and its substrate is necessary. The use of geophysics, in conjunction with geotechnical
36 probing, allow the project owner to greatly enhance the knowledge of the project's plot. The
37 advantages of geophysics are its non-invasiveness, completeness and rapidity: surveys can be
38 done over the entire studied field in order to describe underground properties variations
39 without digging within a few days. Geotechnical soundings, like drilled hole, can be
40 performed later on to help interpreting the observed anomalies. Using this approach has two
41 advantages. Firstly, it reduces drastically the number of boreholes needed, thus reducing the
42 time and cost of the operation. Secondly, it reduces the risk to completely miss a structure
43 thanks to the continuous vision offered by geophysics mapping. This approach is nowadays
44 largely accepted for near surface investigations (Ward, 1990): information about the
45 increasing role played by electromagnetic induction methods (EMI) for hydrologic
46 applications can be found in (Bendjoudi et al., 2002; Boaga, 2017), for soil studies in (Corwin

& Lesch, 2005; Doolittle & Brevik, 2014), for superficial geology mapping in (Saey et al., 2008), and for brownfields in (Cavalcante Fraga et al., 2019; Guérin et al., 2004) for example.

The use of EMI in the present case study is relevant, because this method is sensitive to several electromagnetic properties and may inform about two of main sources of uncertainties: that are the one related to the variations of the substrate (Dabas et al., 2016), and the presence of metallic features (Thiesson et al., 2018). We will see, through this example, how geophysics has contributed to the global knowledge of this construction project, and particularly the contribution of EMI data.

Site overview

The context of the case study is the expansion of a commercial area. It takes place in Vienne department, near Poitiers, in western France. In 2009, when the geophysical study was commissioned, the field was agricultural land, surrounded on the west side by a motorway, and various building and installations on the other sides (**Erreur ! Source du renvoi introuvable.**A). The project owner intended to extend the commercial area in this field. Geocarta was the company in charge of the geophysical survey. A potential risk of unknown and problematic features was suspected. From a geological point of view, the bedrock of the area is mostly made of limestones. Karstic structures are known in the vicinity of the studied area and may imply the discovery of cavities during the construction (BRGM, 1974). Moreover, the nearby city, Chasseneuil-du-Poitou, contains a lot of archaeological remains and a few ancient human occupation traces were found during excavations north of the field. It is consequently not possible to ensure the absence of archaeological entities in the area of interest. There could also exist industrial hazards: the project owner discovered a battery storage site near the expansion zone.

Before the geophysical prospection, the only available data were the geological map and several aerial photographs. A geotechnical campaign was also done just before the geophysical survey, but the results were only available after the first geophysical map interpretations. The disturbances generated by this campaign and its incidence on soil structure may be visible on the geophysical maps, so they will be presented first to avoid discussing on irrelevant anomalies.

The geological map indicates a transition between two units on the field, which roughly follows the altimetry. The upper unit on the west is limestone (J6a on **Erreur ! Source du renvoi introuvable.B**), with a variable composition comprising gravel and oolites (BRGM, 1974). Layers of slightly different limestones can alternate in this unit. The lower one, at the east (J4-5), corresponds to a fine gravel limestone fabric. The presence of limestone may imply the presence of natural karst cavities. The transition between these two units in the field may induce a variation of the geophysical/geotechnical properties.

On the aerial photograph taken during the spring before the survey, several clues of subsurface structures are visible (**Erreur ! Source du renvoi introuvable.C**). The differences in crop colours are mainly linked to the soil capacity to sustain their growth (Available Water Capacity). It is possible in some circumstances, like on this picture, to detect geological heterogeneities using these contrasts of colours. This image shows a rather complex geological context. In particular, the transition between the two geological units is visible. The central zone, with the alternation of green and yellow stripes aligned with the expected transition, is more likely due to small scale variations within the limestones (j4-5) unit. These layers are probably sub-horizontal, because the alternation roughly follows the altimetry.

The geotechnical campaign done prior to the geophysical prospection consisted in 158 boreholes and 15 pits dug by power shovel, mainly located in the northern-east part of the plot (P1 to P15, **Erreur ! Source du renvoi introuvable.**). The boreholes were unfortunately not

georeferenced, so they were unusable for this study. The pits were located along the proposed road plan to determine the ability of the substrate to endure the associated strain. All pits had a depth of around 2 metres. The results indicate a homogeneous limestone substrate. This is certainly because the required precision of the geotechnical campaign in facies recognition is below the degree of variation predicted from the geological map and observed from the aerial photograph. Two critical structures were nevertheless found: the first one is a sand pocket in the pit P4, under altered limestone, with its top at 1.2 m below surface. The second one is a karstic void in P11, starting at a depth of 1.2 m. Failing to predict the location of other similar features can seriously endanger the construction process.

Methods

Three geophysical methods were deployed on this field, to capture as much information as possible. The first one is an electrical resistivity measurement method with an Automated Resistivity Profiling (ARP) system (Dabas, 2009), the second one is a magnetic gradient measurement method and the third one an electromagnetic induction method (EMI) (**Erreur ! Source du renvoi introuvable.**).

The ARP instrument (Géocarta, Paris, France) used in this study allows to take continuous measurement of electrical resistivity while driving with an in-line sampling interval of 0.1m, each spiked wheel acting as an electrode. The ARP is widely used for archaeological surveys as well as agricultural plot characterisation. The method is mainly influenced by bedrock depth, soil compaction, granularity and water content (either a frozen ground or a very dry soil avoid electrical measurements). It is not, however, sensitive to the presence of buried metallic features. The main limitations for using ARP are the need of a soft and humid ground

to operate, and the limited vertical extent of its depth of investigation (1.7m), which in this case reduce the probability of finding cavities.

The device used for magnetic measurements is a cart with five vertical gradiometers (Grad-01-1000L, Bartington, Oxford UK). They are placed perpendicular to the survey direction with a 0.5m cross-line separation. This method is sensitive to lateral variations of the magnetic field produced by changes in the ground magnetic susceptibility and in remanent magnetizations. Huge variations of magnetic field in soils can originate from ferromagnetic elements like iron litters, rock boulders containing iron oxides, but also human artefacts like burnt clays. Some geological variations, especially sharper ones like faults, can also be detected. It is however insensitive to non-ferromagnetic metals like aluminium or copper and the depth of investigation is highly dependent on the geometry and the size of objects.

The EMI device used in this study is also mounted on a cart. The device used (DualEM 4S, DualEM Inc., Milton, Canada), is a 9 kHz mono frequency EMI with a horizontal emitting coil, *i.e.* a vertical magnetic dipole. It has two receiving coils, with respectively horizontal coplanar (HCP) and perpendicular (PRP) orientations located at 4.0 and 4.1 meters from the emission. The cart maintains the device at constant height above ground surface (28 cm). This method is sensitive to three different properties of the soil: electrical resistivity/conductivity, magnetic susceptibility and dielectric permittivity. Over sedimentary formations, the major part of the signal comes from the ground conductivity but measurements can be heavily affected by the presence of buried metals. But EM instruments are able also to detect non-magnetic metallic objects (Nabighian, 1991; Ward & Hohmann, 1988). Due to the higher depth of investigation compared to the ARP (6 m for the HCP coil), the signal representing a deeper portion of the subsurface, the response of surficial targets is lowered. The main difficulty working with EM data is to separate the susceptibility and permittivity-induced

responses that are both in-phase with primary field and of lower amplitude than the conductivity response.

Geophysical results: qualitative assessment

All geophysical data were acquired in December 2009. The procedure was to follow parallel profiles spaced by a certain distance which depends of the used method. Along the profile, data were acquired at a 10 Hz rate for the EMI and 80Hz for the gradiometers. To have a high data density, a small distance between two profiles was chosen: 1m for the ARP, 2.5 m for the gradiometers (which results in an across-line spacing of 0.5m with the 5 probes cart), and 2 m for the EMI. All data are positioned thanks to a real time kinematic (RTK) positioning system, consisting in a base station radio-linked to the mobile rover fixed on the survey cart. This system provides an accuracy around 1 cm. Acquisition of these three sets of data was done in three days (14 ha).

These data were first processed, especially to remove outlier values. Then, they were interpolated to generate an image for each type of data (or layer in GIS vocabulary), with a colour map fitted to the dynamic of this layer in order to improve the readability of the result. The interpolation method used was a spline MBA method (Lee et al., 1997). The first results of the survey will be discussed using these images. Data visualisation is crucial to get the most information as possible from the data. The choice of the pixel's size is one of the main parameters. In fact, too big pixels reduce the amount of information present on the images, and too small ones give the interpreter a feel of precision higher than the real capabilities of devices, as well as an increasing of the computer memory necessary to processing the data. Empirically, the images have a pixel size from one third to half of the crossline spacing. The

165 images presented here have a pixel size of 0.3 m for the ARP, 0.25 m for the magnetism and
166 0.60 m for the EMI.

167 The three ARP maps show coherent structures in regard to the aerial photo and the geological
168 map (**Erreur ! Source du renvoi introuvable.** just shows the intermediate depth of
169 investigation). In particular, the transition from the resistant area r1 to the resistant area r6
170 through the more conductive area r2 corresponds well to the transition between the j6a and j4-
171 5 units (**Erreur ! Source du renvoi introuvable.**). The possible paleochannel on the aerial
172 photo is also related to the anomaly r5. However, the resistivity maps exhibit greater
173 variability and more details than expected by the aerial map. On the area r1 of the map, a lot
174 of blue 'dots' are visible (conductive areas below 40 Ohm.m), and overall, a little bit of noise
175 is visible on most of the maps. This is partly due to the survey conditions, as the ground was
176 frozen in some areas, increasing the contact resistance between the wheels and the ground.
177 But this noise is also a source of information: for instance, the area r1 presents a lot of
178 conductive points, which is indicative of a surface state different from the rest of the field. In
179 this case, this is certainly due to a higher stone content in the surface layer in area r1,
180 disturbing the contact of the wheels with the ground. There is also a thin noisy line
181 corresponding to the paths of the excavator when it reached the pit sites. The most significant
182 one extends between P5, P6, P7, P12, P13 and P14. The compaction due to the heavy load of
183 excavator have modified the surface state of the field changing its electrical resistivity.

184 The magnetic map brings different results (**Erreur ! Source du renvoi introuvable.**): there
185 still exist similarities with the resistivity map, like the set of linear anomalies oriented NW-
186 SE, visible on both and tagged g3 on the magnetic map. The possible paleochannel gives also
187 a well-defined positive magnetic response. But magnetic gradient shows several zones rich in
188 ferromagnetic dipoles, that may form a compact unit (anomaly g2), or outline an area
189 (anomaly g4), or are aligned (anomaly g6). We can also notice other lines, rather similar to

190 the anomaly g3 but oriented SW-NE instead. There are also strong responses at the borders
191 of the field which are due to external metallic objects. This noise is either coherent (g1,
192 metallic fences) or incoherent due to heavy traffic of lorries and cars close to the motorway (a
193 linear band of roughly 30m wide parallel to the N-S direction of the motorway). We can also
194 notice a circular anomaly, positive at the centre and negative around, 60 meters south of the
195 anomaly g4 that is due to a utility pole.

196 Conductivity mapping corresponds to the major specifications the stakeholder most often asks
197 for when EMI is used. On this field, both HCP and PRP (4.1 and 2m DOI respectively)
198 configurations are equivalent in terms of qualitative assessment of information (**Erreur !**
199 **Source du renvoi introuvable.**). Because there is no need of a galvanic contact with the soil,
200 the map shows far less noise than the ARP one. Like in the magnetic method, the fences
201 around the field induce a strong signal along the edges of the map, even if the effect is here
202 less pronounced. Most of the variations corroborate the ones observed with the ARP
203 (anomalies matching: c1-r1, c2-r2, c3-r5, c4-r4, c6-r6). It is fortunate that the P4 pit was dug
204 precisely in the conductive anomaly c5: this allows to interpret the conductive anomaly by the
205 presence of fine sand/clay pockets located at a depth close to 1 m. Some elements are more
206 marked on the EMI map than on the resistivity map (anomaly c4), while some others are more
207 blurred, in particular the layered area c2. There are two main anomalies only visible with the
208 EMI: first, a conductive anomaly crossing the eastern part of the structure c3; second, a
209 conductive anomaly that we will describe as a ‘radially striped disk’ of 70m in diameter
210 (anomaly c7). This very enigmatic feature has for the greater part of its surface a high
211 conductivity, around 30 to 40 mS/m, while the rest exhibits negative conductivity readings.
212 These characterize the presence of one or of a group of metallic features. This interpretation is
213 corroborated by the absence of anomaly in the ARP maps. On the magnetic gradient map

several distinct huge dipolar anomalies correspond to the same location (**Erreur ! Source du renvoi introuvable.**).

The HCP conductivity map is similar to the PRP one. We can still notice some differences: the linear anomalies oriented NW-SE (c4), are more visible on this map than with the PRP configuration or with the ARP. They certainly are narrow conductive structures, as their response in their centre have an inverted sign, which in HCP configuration, corresponds to features which have smaller width than the inter-coil distance. It is probable that these anomalies denote an elongated structure filled with sediments similar to those observed in P4 pit. The enigmatic ‘radially striped disk’ feature looks divided into four quarters like a pie: two conductive and two resistive. This confirms the presence of a bulky metallic structure. However, as this corresponding global layout is not observable in the magnetic gradient map (**Erreur ! Source du renvoi introuvable.**), the metal must be non-magnetic.

With the EMI data, it is also possible to compute both magnetic susceptibility and dielectric permittivity maps. In this case study however, the only relevant map is the permittivity one (

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Appendix A). While of significantly different global layout, some anomalies visible on the conductivity/resistivity maps are again encountered (**Erreur ! Source du renvoi introuvable.**). The anomaly e2 corresponds to the lines tagged as g5 on the magnetic map (**Erreur ! Source du renvoi introuvable.**) while the anomaly e3 matches to the paths of the excavator between some pit sites, and is therefore caused by ground compaction. The anomaly e6, that connect the lines forming the anomaly g5 on the magnetic map have the same signature as the anomaly e2, and are thus certainly of the same kind. The enigmatic disc shaped anomaly, noted e4 on this map, is clearly marked by extremes values compared to the field. It is known that, in presence of metal objects, one cannot interpret the results in terms of soil properties and a global interpretation is necessary to determine the object shape and characteristics (Thiesson et al., 2018). The anomaly e1 is a set of three small zones with higher permittivity. When superimposed with the geotechnical pit's locations, it is clear that they correspond to three of them. Moreover, all the pits are more or less closely correlated with higher permittivity anomalies. These anomalies are a footprint of the soil reorganisation and compaction caused by the excavation.

306 Combined interpretation

307 The multi-method geophysical survey highlights a great number of structures. Based on
308 apparent property maps, some are already interpreted, they are listed in **Erreur ! Source du**
309 **renvoi introuvable.**, excluding the ones identified as remanences of the geotechnical study.
310 They have mainly a geological origin, which is an important conclusion in the perspective of
311 future constructions. For example, in the central part, three geological units are identified,
312 including one layered outcrop. The structure around the pit P4 shows a sand infilling under a
313 limestone roof. The conductive zones nearby probably are the signature of similar structures.

314 The composite bands method was used to create a synthetic map of the geophysical surveys
315 (**Erreur ! Source du renvoi introuvable.**). This display allows to show simultaneously three
316 layers of data. In this case one layer from each geophysical method. It is commonly used to
317 visualize satellite images, where a great number of bands are acquired simultaneously. Thanks
318 to this method, it is possible to display more features of interest on a single map. The
319 drawback is the difficulty of reading the values from the colours. However, it is a useful tool
320 to synthetize the information, at the cost of some readability about the absolute values.
321 Nevertheless, the composite bands map contains exactly as much information as the maps in
322 each band. It guarantees that a specific colour corresponds to one single triplet of values, and
323 allows to observe contrasts efficiently. The other important point to understand about this
324 visualisation is that red, green, and blue colors as not perceived the same way by human eyes.
325 These are more sensitive to green, then red, and blue. To have a readable map, it is important
326 to affect the map with the most valuable data to the green channel, and the one that has the
327 less valuable information on the blue. As the EMI and ARP maps are quite similar, and we
328 want to focus more on the EMI, the green channel corresponds to EMI, the red one to
329 magnetism and the blue one to ARP. With these settings, it is possible to see almost all the
330 anomalies previously described on the same image.

331

332 Further interpretation

333 The three investigation techniques exerted on this site clearly evidence lateral variations
334 associated with both natural and artificial causes. However, the interpretation based on
335 apparent property maps does not inform about the location in depth of the causative features
336 and as we have at our disposal five different measurements of the apparent
337 resistivity/conductivity corresponding to five different depths of investigation (three with the
338 ARP and two with the DualEM4s), it is possible and interesting to attempt assessing the
339 location in depth of the features corresponding to resistivity/conductivity changes. To this
340 aim, we have resampled each set of data on a $2 \times 2 \text{ m}^2$ grid and inverted them using a simple
341 1D model at each location where the five measurements exist and are not affected by metallic
342 responses. The 1D inversion uses an analytic forward modelling and inverse solutions are
343 stabilized thanks to a Marquardt-Levenberg scheme. We have used a three-layer model with
344 five unknowns: the thickness and resistivity of a first 'soil' layer, the thickness and resistivity
345 of a second 'subsoil' layer and the resistivity of the third 'substrate' layer. In a first step, it is
346 possible to fix two thicknesses to observe in which layer the inversion process locates the
347 most important change of resistivity. Then, to reconsider the thickness value of the subsoil
348 and repeat this approach in order to grasp the location in depth of the resistivity variations. As
349 observed in **Erreur ! Source du renvoi introuvable.**, which corresponds to the case where
350 the soil thickness is fixed to 0.3 m and the subsoil thickness to 0.7 m, the inversion always
351 addresses the most part of the variations to the subsoil layer. One can thus propose that both
352 the alternate resistivity strips in the central part and the higher resistivity area in the northern
353 part outcrops are just below the soil layer.

354 External sources of information can also help understanding the nature of the geophysical
355 anomalies. In this regard, aerial photographs are a valued source of information. In France, it

356 is now possible to access freely a great number of campaigns, since the first one in 1919
357 (<https://remonterletemps.ign.fr/>). Here, three photographs were selected, those acquired in
358 1945, 1965 and 2002.

359 At the time of the oldest photograph (1945) (**Erreur ! Source du renvoi introuvable.**), the
360 area was purely agricultural, apart from the road that today crosses the commercial zone,
361 visible on the eastern edge of the picture. The field layout of this period has left traces on the
362 geophysical map, especially on the magnetic one in the central part of the field. Some offset
363 between the image features and the geophysical anomalies, are mainly due to the photograph
364 distortion. The anomaly g9 can still be correlated to a road, and corresponds to one of the two
365 linear structures tagged as M (**Erreur ! Source du renvoi introuvable.**). The anomaly g5 is
366 oriented along the field's limits, and corresponds to the structure J. We can propose here that
367 the structure J and a part of M are due to previous land use, and might cover small buried
368 objects. The fact that they are only visible on the magnetic map but with a weak signal
369 suggests that no metal is associated with them.

370 The two other photographs (taken in 1965 and 2002) display other structures that can be
371 correlated to geophysical anomalies (**Erreur ! Source du renvoi introuvable.**). The fragment
372 of land marked a2 is at the same place as the anomaly H, which groups many small dipoles.
373 As it was not used in 2002 as agricultural land and considering the signal, it seems like an
374 area rich in buried metallic elements. The structure a3, a field limit, fits with the part of the
375 anomaly M which has no correspondence with the 1945 photograph (**Erreur ! Source du**
376 **renvoi introuvable.**). The building a1 is in fact an antenna, with associated structures. Most
377 of them are still visible on the magnetic map, like the cable route between the antenna and the
378 road. We can also see anomalies corresponding to the 6 anchorage points of the antenna, on 3
379 axes around it, which are visible on the aerial map after an important zoom in. So, the
380 underground part of these elements was still in place in 2009. A similar signature is also

381 perceptible on the EMI map (**Erreur ! Source du renvoi introuvable.**), but is not
382 interpretable without external information. This is due to the strong ‘radially striped disk’
383 anomaly, which overrides the signal in the area. This anomaly doesn’t correspond to any
384 surface structure. It is then probably buried and in relation with the antenna. Due to the
385 intensity of the signal in both EMI configurations and its lack in magnetic gradient, this is a
386 metallic, non-ferromagnetic grid or extended sheet.

387 These photographs may indicate possible origins of some of the anomalies, but uncertain
388 elements remain: we can make some hypothesis, but interpretation will be less robust than
389 with external information. For example, the structures I and L are rather localised and are
390 sharp; it is possible to propose an anthropic origin, like fields limits, maybe with some fence
391 fragments. We can see a north-south discontinuity on the HCP EMI map just west of the
392 “antenna plate”, on the axis of the ARP r3 anomaly (**Erreur ! Source du renvoi introuvable.**
393 and **Erreur ! Source du renvoi introuvable.**). These elements may lead us to consider the
394 existence of a fault, with a displacement of about 60 meters (**Erreur ! Source du renvoi**
395 **introuvable.**). This hypothesis is motivated by the existence of a known fault with same
396 orientation 8 km westward. If this is a fault, we can consider the linear structures marked as D
397 (**Erreur ! Source du renvoi introuvable.**) as secondary faults or joint, associated with little
398 or no displacement. The conductive nature of these structures can indicate that they are filled
399 with a finer material, as observed in the P4 pit. The observed variability in the amplitude of
400 the signal from these anomalies can have two origins: firstly, they can have a variable width,
401 inducing a different amount of infilling material; secondly, some portion could be empty due
402 to some karstic activity. These structures might be correlated in that case with cavities.

403 The nature of the enigmatic ‘radially striped disk’ anomaly was confirmed by the
404 archaeological diagnosis conducted a few months after the geophysical survey. Six anchorage
405 points in reinforced concrete were found at the location of magnetic anomalies. The signal

visible on the EMI came from a radial copper mesh, buried at 70 cm depth. This kind of mesh is commonly used as grounding systems for antennas. No other major structure was found in the field. However, the diagnosis only concerned the northern part of the field, so the nature of the anomalies E and L is not confirmed yet.

All the anomalies have now an interpretation (**Erreur ! Source du renvoi introuvable.**). The main hazards for the construction operations to consider were:

- the variation of the substrate nature.
- the presence of sand pockets in the north western part of the field.
- the faults or joints, that imply a different substrate material, and a risk of cavities.
- the remains of the antenna in the centre of the field.

Discussion

The geophysical survey detected numerous features, and the causes of almost all anomalies were found, through geophysical interpretation, direct observation or historical research. However, some uncertainties remain. The nature of anomaly I remains unknown, but it is certainly an anthropic feature. Still, the most uncertain feature is the nature of anomalies C and D. The proposed interpretation fits the available data, but no direct verification has been done.

The other apparent weak point of the survey is the absence of detected cavity, while one was found in the pit P11 (**Erreur ! Source du renvoi introuvable.**). Several reason may explain this. Firstly, the specific cavity, due to its small dimensions (around 1.2 m of diameter at 1.2 m depth), was certainly filled during by the filling of the pit. In addition, it is probable that similar cavities would create a signal below the level of detection of the devices used. So, the likelihood to detect this kind of features is low. Thirdly, this cavity was found near an edge in

the lower part of the field. It is possible that a hypothetical karstic network under the field would be located at a depth beneath investigation abilities of the used methods.

Conclusion

The case study presented in this paper was achieved in real conditions: in a limited time, at an unfavourable season, with geotechnical excavations achieved just before the geophysical investigation and not after, and in a noisy context. In spite of these conditions, it illustrates the advantage of the confrontation of several geophysical methods in land planning. The three methods used in this example were adopted because of their ability to rapidly map several hectares with a high measurement density. The use of several methods improves greatly the quality of the interpretation for two main reasons: firstly, it increases the number of measured soil independent properties, the variations of which are related to different underground characteristics. Secondly, when the same properties are obtained by two different methods, it authorises a higher degree of confidence in the subsurface structure's type identification. The use of an EMI was completely justified in this case, because it is sensitive to several soil properties and because of its ability to detect metals and to separate ferrous and no-ferrous items. Using it together with the electrical and magnetic methods allows two independent recording of electric conductivity and magnetic susceptibility variations. The survey on the Grands Philambins shows the complementarity of these methods. The electrical survey gave the most detailed conductivity map, at the cost of the depth of investigation (less than 2 m). The magnetic survey detected the old field boundaries, and ferrous objects precisely. The EMI added major pieces of information. Two independent conductivity maps with higher depth of investigation permitted to better assess geological features. In addition, the sensitivity of the EMI to any kind of metal, at the contrary to the magnetics only sensitive to ferrous element, is useful to identify recent anthropic features indicating the metal type. It thus resolved the

Grands Philambins enigma. The dielectric permittivity map calculated from the EMI data was also very sensitive to recent soil compaction and reorganisation.

The EMI in geophysical technique well matches with land planning studies. It is efficient to detect several kinds of underground variations, from the substrate modification to the presence of buried metallic objects. Its use in conjunction with other, like electrical and magnetic method, drastically increases the subsurface comprehension.

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Figures and tables captions

Figure 1: overview of the survey site. A) area of interest and its surrounding. The zone of extension of commercial area is in turquoise blue and is about 14 ha. We can see, on the west side, the A10 motorway, the commercial area to be extended on the east, a karting track in the north and a housing development in the south. Inside the turquoise area, the altitude varies from 90 meters on the eastern side to 110 meters on the north-western corner. B) map of the geological context. The prospection area is split between two geological units, j6a and j4-5.

These units are two types of limestones. The slope of terrain implies that the j4-5 layer is buried below the j6a layer on the north-western part of the terrain. Geological survey map also indicates karstic structures in the region, with no precise indication for this area. (Source of A and B: <https://www.geoportail.gouv.fr/>). C) aerial view of the terrain. The approximate prospection zone is outlined in red. Along all the aerial pictures of the site, this one is the most interesting because it is possible to see, through the variation of crop colours, some geological structures. One highlight is the transition between the two geological units expected on the left part of field. The j6a unit, which is along the western edge, seems homogeneous, while j4-5 unit, at the east looks more heterogeneous: the alternation between at least two layers, which are roughly aligned with the topography, are certainly part of the j4-5 unit. On the south of the field, a horizontal line of darker vegetation may be the sign of a paleochannel.

Figure 2: Photographs of the three devices used in the survey. A) Automatic Resistivity Profiling (Géocarta, Paris, France). The cart pulls 4 pairs of wheels acting as 4 pairs of electrodes. The first pair injects the electrical current in the ground. The various spacing between this pair and the three others allow to measure the voltages corresponding to three different investigation depths (0.5, 1 and 1.7m). B) magnetic gradiometry device. The five probes (Grad-01-1000L, Bartington) are placed vertically in order to measure the pseudo-gradient on the vertical component of the Earth Magnetic Field. The spacing between probes is 0.5m. C) EMI cart. The device used here is the multi orientation mono frequency DualEM 4S (DualEM Inc, Canada).

Figure 3: one of the apparent resistivity maps obtained with the ARP, with a depth of investigation of 1 m, superimposed with the geotechnical soundings. The pits are numbered P1 to P15. Many structures are visible on the geophysical map, and the most significant ones are tagged. r1: resistant and rather homogeneous zone. r2: alternation between conductive and slightly more resistant linear structures. r3: linear conductive anomaly, oriented W-E. r4: one of conductive and very thin anomalies, oriented NW-SE. They are more visible in the area r1, but a close look on data indicates they cross all the field. r5: 10 meters wide conductive anomaly, oriented W-E. r6: heterogeneous area, more resistive in average than r2 but less than r1.

Figure 4: magnetic vertical gradient map. Many structures are visible, and the most significant ones are tagged. g1: an intense anomaly covering some of the edges of mapped zone. g2: noisy and triangular structure, composed of many small dipoles. g3: one of the linear anomalies oriented NW-SE, with a variable intensity response. g4: a set of positive anomalies forming the edge of a trapezoid like structure. g5: one of linear anomalies oriented SW-NE, with a low but steady response. They are almost perfectly aligned with altitude contours. g6: group of strong dipoles, forming lines. g7: a linear positive WE anomaly. g8: a linear anomaly with a low but steady signal and a sharp angle. g9: one of two linear anomalies, roughly oriented WE, with a weak but steady response.

Figure 5: EMI conductivity maps (left: PRP, right: HCP configuration). Both maps show mainly the same structures. Most significant anomalies are tagged. c1: resistant and rather homogeneous zone. c2: conductive zone, with light periodic variations on a SW-NE direction. c3: 10 meters wide conductive anomaly, oriented W-E. c4: one of conductive and very thin

anomalies, oriented NW-SE. They are more visible in the area c1, but a close look on data indicates they cross all the field. c5: elongated conductive anomalies, certainly of the same nature as anomaly c4. c6: heterogeneous area, more resistive in average than c2 but less than c1. c7: very conductive structure like a 'radially striped disk', of about 70 metres in diameter. The pit P4, located in a conductive anomaly, is also shown.

Figure 6: relative permittivity map, most significant anomalies are tagged. e1: set of high permittivity points. e2: one of two low permittivity lines, oriented SW-NE. e3: thin anomaly with high permittivity, with a curve shape. e4: radially striped disc with very high signal variation. e5: 10 meters wide anomaly, oriented W-E. e6: one of two low permittivity lines, oriented NW-SE and connecting the lines of the e2 anomaly. The black dots represent the location of the pits dug before the geophysical survey.

Figure 7: composite bands map of the geophysical survey. This method takes advantage of the fact that any colour can be decomposed in red, green and blue. It is then possible to superimpose up to three layers of information on the same map. Each layer determines what intensity of respectively red, green and blue is applied to each pixel. The structures placed are described in Table 1.

Figure 8: 1D model calculated by inversion with the ARP and EMI conductivity data. On the soil map, the effect of the surface condition is clearly visible because of great sensitivity of the ARP to surface state variations. It is also visible that the variation is mainly concentrated in the subsoil layer. In fact, the resistivity varies from 30 to 250 $\Omega.m$ in the top soil and substrate layer, against a variation between 30 and 600 $\Omega.m$ in the subsoil layer.

549

550 Figure 9: aerial photograph of the terrain in 1945. Some anomalies, especially on the
551 magnetic map, are correlated with the structures from this time. Mainly, the anomaly g9
552 corresponds to a small lane, and linear anomalies like g5 seem correlated to field limits. The
553 anomalies don't correspond exactly to the aerial image because it is heavily distorted,
554 inducing approximate georeferencing.

555

556 Figure 10: aerial photographs taken in 1965 and 2002. Several structures are correlated to
557 geophysical anomalies. a1: antenna with associated infrastructures, like a road, a little
558 building and a set of anchorage points (when zoomed in). a2: triangular field not used as
559 agricultural land. a3: field limit, certainly an agricultural path too.

560

561 Figure 11: composite bands map of geological features. The layers used are the one that are
562 sensitive to geological variations, which are the ARP and the EMI conductivity maps. On the
563 left side, we can see just west of the disc anomaly a straight line almost WE. This line is
564 mainly visible on ARP. On the right side, the southern part of the map has been shifted of 63
565 meters to the west. This way, we can see a continuity on the layers of the central geological
566 unit, here in pale blue. The anomaly visible on ARP might then be a fault. Unfortunately, its
567 location close to the edge of the prospection and the presence of a strong anomaly on EMI
568 nearby reduces the readability.

569

570 Figure 12: DualEM with $h=0.28\text{m}$, $L=4\text{ m}$ (HCP), $L=4.1\text{ m}$ (PRP) and $f=9\text{ kHz}$. Variations of
571 the in-phase responses for a homogeneous ground where $\sigma=0.02\text{ S.m}^{-1}$ with the magnetic

susceptibility (for $\epsilon_r = 200$) on the top and with the effective relative permittivity (for $\kappa_{ph} = 50$ 10-5 SI) on the bottom.

Figure 13: comparison of properties calculated from magnetic and EMI data on a specific area. Z magnetic gradient map, acquired with the AMP. Equivalent stratum susceptibility variation) susceptibility variations computed from the Z gradient map. DualEM susceptibility map computed from in-phase data. DualEM relative permittivity map computed from in-phase data.

Table 1: recap of the observed structures on the geophysical survey and their interpretations based only on the geological context and the contemporary aerial photograph of the site.

Table 2: table of structures interpretation. The ones with no source indicated were deduced from the geophysical survey only, and are less robust.

Table 3: coefficients and offsets used in order to compute the magnetic susceptibility and dielectric permittivity maps. The slopes were obtained through the calculation of the responses above a homogeneous media, while the offsets were obtained to get likely final positive values. The offset values don't need to be accurate in this application, because they don't affect the variations of the properties but only their absolute values.

Conflict of Interest and data availability statement

Data sharing not applicable - no new data generated.

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Appendix A

Processing of EMI data

To extract from the EMI data more complete information than the conductivity maps, some processing is necessary. In fact, the DualEM 4S outputs two values by receiver coil, the in-phase signal and the quadrature out of phase signal. A good zero calibration can be assumed for the out of phase quadrature signal (auto-calibration designed by the manufacturer). While in the in-phase component huge signals may result from an improper compensation of the primary field and would necessitate an in-field calibration during each portion of a survey

(Thiesson et al., 2014). In fact, for the in-phase component, the auto-calibration is refreshed at every restart of the device, leading to huge offsets between the different portions of a survey.

The ground response is expressed by the ratio H_s/H_p between the secondary field, produced by the soil, and the transmitted field at the receiver location. The determination of the apparent properties must be achieved using the complete analytical expressions of the secondary fields (Thiesson et al., 2014; Ward & Hohmann, 1988) but simple approximate expressions may facilitate the understanding of the role of each physical property (J. D. McNeill, 1980). Assuming a null clearance, $h=0$, above ground surface, one has when the frequency tends to 0 for the magnetic susceptibility responses, $\frac{H_s}{H_p} \cong -\frac{\kappa}{2}$ for HCP and 0 for PRP (but differing from 0 for $h \neq 0$).

Under the Low Induction Number (LIN) approximation, considering both the conductivity and the permittivity and assuming a null susceptibility one has:

$$\frac{H_s}{H_p} \cong -\frac{i\sigma\mu_0\omega L^2}{4} + \frac{\varepsilon\mu_0\omega^2 L^2}{4} \quad \#(1)$$

In these expressions, L is the distance between transmitting and receiving coils, σ the homogeneous ground conductivity, ω the angular frequency of the primary field and μ_0 the free space magnetic permeability. $\kappa = \kappa_{ph} - i\kappa_{qh}$ is the magnetic susceptibility, related to the relative magnetic permeability by the expression $\mu_r = 1 + \kappa$ and to the ground permeability by $\mu = \mu_0\mu_r$. $\varepsilon = \varepsilon_0\varepsilon_r$ is the effective permittivity of the homogeneous ground, product of the free space permittivity ε_0 and relative permittivity, ε_r .

The device measures the in-phase responses, real part, and the quadrature responses, imaginary part, for each receiver coils. Under the above approximations we could see that the conductivity would impact the quadrature component of the signal while ε_r and κ_{ph} would impact the in-phase one. The complete analytical calculation for a homogeneous ground

implies Hankel transforms calculation to obtain the precise role of each property on both components of the secondary field. To determine susceptibility and permittivity responses, one has to remove the effect of conductivity from the in-phase signal. To do this with the DualEM 4S, we assume the quadrature signal to be purely a conductive response (κ_{qu} is neglected) and calculate the corresponding in-phase component which is subtracted. Once it is done, the residual in-phase response depends on 3 variables:

- the in-phase magnetic susceptibility
- the relative permittivity
- and, in absence of zero calibration, the in-phase offset

For the low frequency range and common soil and rock properties, the complete calculation establishes that the in-phase signal is linearly proportional to magnetic susceptibility and to relative permittivity (Benech et al., 2016) with slopes depending on the geometry of the device. This is illustrated in **Erreur ! Source du renvoi introuvable.** where are shown for a homogeneous ground of 0.02 S.m^{-1} conductivity the variations of the in-phase responses with the magnetic susceptibility (for $\epsilon_r=200$) one the one hand and with the effective relative permittivity (for $\kappa_{ph}=50 \cdot 10^{-5} \text{ SI}$) on the other hand.

Knowing these slopes, it is possible to write:

$$\begin{cases} \text{Re} \left(\frac{H_s}{H_p} \right)_{HCP} = \text{Off}_{HCP} + C_{HE}\epsilon_r + C_{HK}\kappa_{ph} \\\\ \text{Re} \left(\frac{H_s}{H_p} \right)_{PRP} = \text{Off}_{PRP} + C_{PE}\epsilon_r + C_{PK}\kappa_{ph} \end{cases} \quad \#(2)$$

If the offsets are determined, it is possible with this set of two equations to find the relative permittivity and the magnetic susceptibility of a homogeneous ground. For the current application, in absence of in-field calibration, the focus is to map the variations of these parameters. So, the offsets have been arbitrarily chosen to get positive values of both apparent

properties and a likely ratio between the interquartile difference and the median values for each property. The resulting values and the slope coefficients are presented in **Erreur ! Source du renvoi introuvable.**

For a 4m spacing and 9 kHz frequency EMI one cannot consider that the in-phase response is dominated either by the magnetic susceptibility or by the permittivity. Considering the high correlation between the two apparent property maps (**Erreur ! Source du renvoi introuvable.**), it is likely that both maps exhibit the variations of the same of the two properties and that the separation process has failed, but it is also far from impossible that both properties are correlated. To identify the possibly dominant it is possible to transform the magnetic gradient map into an equivalent magnetic stratum (Desvignes et al., 1999) and compare it to the EMI magnetic susceptibility map.

The gradient data were extracted from a rectangular zone in the central area with a 2 m x 2 m measurement mesh and the equivalent magnetic stratum was computed. The **Erreur ! Source du renvoi introuvable.** shows the magnetic gradient, the corresponding magnetic susceptibility variations of the equivalent stratum centred at 0.5 in depth and 0.5 m thick, the DualEM magnetic susceptibility and the DualEM relative permittivity. The spatial correlation between the two last is clear but it is not 100%. The spatial correlation between the equivalent stratum variations and the DualEM susceptibility map is low. The interquartile of the equivalent stratum susceptibility variations is $8.3 \cdot 10^{-5}$ SI while that of the DualEM susceptibility is $27.3 \cdot 10^{-5}$ SI. When one changes the depth and the thickness of the equivalent stratum there is no significant change of the interquartile. As the equivalent magnetic stratum may contain a part of remanent magnetisation (mainly the viscous one) its susceptibility variations might normally surpass that of the DualEM.

In conclusion, if one of the two properties is dominant in the in-phase measurements, it would be the permittivity. For this reason, the susceptibility map is not showed in the present case

735 study. Another case has been published (Simon et al., 2020) where the same difficulty has
736 been met for EM31 measurement interpretation. There considering the very high magnetic
737 susceptibility, the conclusion was in favour of the dominance of the susceptibility.