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

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6 **Abstract**

7 Spatial planning aims at constantly improving the distribution of people and activities within
8 available space, especially near cities on ancient agricultural or industrial areas. However, a
9 proper schedule of the development work necessitates to assess as precisely as possible the
10 difficulties that would be encountered in terms of geotechnical abilities of the terrain and
11 hazards resulting from previous use. In the Grands Philambins site three different geophysical
12 techniques were combined, multi-depths resistivity, magnetic gradiometry and
13 electromagnetic induction (EMI). The aim of this study was to map, in a few days and with
14 high measurement densities, all the EM properties of the terrain and to evidence metallic
15 features. The acquired data were compared with prior documentation, mainly the air photos
16 acquired since the middle of the 20th century. The terrain structure is complex, at the junction
17 of geological formations composed of limestones and marls in different proportions, which
18 were characterised by the geophysical survey. It exhibits also metallic features, among which
19 an enigmatic 70 m diameter radially striped disc object which was identified as non-ferrous
20 and corresponding to an ancient antenna earthed socket. This case study illustrates the
21 relevance of the use of EMI measurements in land planning studies as this method can map
22 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

47 & Lesch, 2005; Doolittle & Brevik, 2014), for superficial geology mapping in (Saey et al.,
48 2008), and for brownfields in (Cavalcante Fraga et al., 2019; Guérin et al., 2004) for example.

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

55 [Site overview](#)

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

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

76 The geological map indicates a transition between two units on the field, which roughly
77 follows the altimetry. The upper unit on the west is limestone (J6a on **Erreur ! Source du**
78 **renvoi introuvable.B**), with a variable composition comprising gravel and oolites (BRGM,
79 1974). Layers of slightly different limestones can alternate in this unit. The lower one, at the
80 east (J4-5), corresponds to a fine gravel limestone fabric. The presence of limestone may
81 imply the presence of natural karst cavities. The transition between these two units in the field
82 may induce a variation of the geophysical/geotechnical properties.

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

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

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

104

105 [Methods](#)

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

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

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

120 The device used for magnetic measurements is a cart with five vertical gradiometers (Grad-
121 01-1000L, Bartington, Oxford UK). They are placed perpendicular to the survey direction
122 with a 0.5m cross-line separation. This method is sensitive to lateral variations of the
123 magnetic field produced by changes in the ground magnetic susceptibility and in remanent
124 magnetizations. Huge variations of magnetic field in soils can originate from ferromagnetic
125 elements like iron litters, rock boulders containing iron oxides, but also human artefacts like
126 burnt clays. Some geological variations, especially sharper ones like faults, can also be
127 detected. It is however insensitive to non-ferromagnetic metals like aluminium or copper and
128 the depth of investigation is highly dependent on the geometry and the size of objects.

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

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

144

145 [Geophysical results: qualitative assessment](#)

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

155 These data were first processed, especially to remove outlier values. Then, they were
156 interpolated to generate an image for each type of data (or layer in GIS vocabulary), with a
157 colour map fitted to the dynamic of this layer in order to improve the readability of the result.
158 The interpolation method used was a spline MBA method (Lee et al., 1997). The first results
159 of the survey will be discussed using these images. Data visualisation is crucial to get the
160 most information as possible from the data. The choice of the pixel's size is one of the main
161 parameters. In fact, too big pixels reduce the amount of information present on the images,
162 and too small ones give the interpreter a feel of precision higher than the real capabilities of
163 devices, as well as an increasing of the computer memory necessary to processing the data.
164 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

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

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

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

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289

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

305

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 x 2 m² 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

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

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

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

416

417 Discussion

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

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

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

432

433 Conclusion

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

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

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

461

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466 the geotechnical survey conducted by ‘AIS centre Atlantique’
467 (<https://www.aiscentreatlantique.fr/>).

468 The authors also wish to thank Alain Tabbagh, for his precious help in the production of this
469 article, through his thoughtful advice and comments.

470

471 [Figures and tables captions](#)

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

478 These units are two types of limestones. The slope of terrain implies that the j4-5 layer is
479 buried below the j6a layer on the north-western part of the terrain. Geological survey map
480 also indicates karstic structures in the region, with no precise indication for this area. (Source
481 of A and B: <https://www.geoportail.gouv.fr/>). C) aerial view of the terrain. The approximate
482 prospection zone is outlined in red. Along all the aerial pictures of the site, this one is the
483 most interesting because it is possible to see, through the variation of crop colours, some
484 geological structures. One highlight is the transition between the two geological units
485 expected on the left part of field. The j6a unit, which is along the western edge, seems
486 homogeneous, while j4-5 unit, at the east looks more heterogeneous: the alternation between
487 at least two layers, which are roughly aligned with the topography, are certainly part of the j4-
488 5 unit. On the south of the field, a horizontal line of darker vegetation may be the sign of a
489 paleochannel.

490

491 Figure 2: Photographs of the three devices used in the survey. A) Automatic Resistivity
492 Profiling (Géocarta, Paris, France). The cart pulls 4 pairs of wheels acting as 4 pairs of
493 electrodes. The first pair injects the electrical current in the ground. The various spacing
494 between this pair and the three others allow to measure the voltages corresponding to three
495 different investigation depths (0.5, 1 and 1.7m). B) magnetic gradiometry device. The five
496 probes (Grad-01-1000L, Bartington) are placed vertically in order to measure the pseudo-
497 gradient on the vertical component of the Earth Magnetic Field. The spacing between probes
498 is 0.5m. C) EMI cart. The device used here is the multi orientation mono frequency DualEM
499 4S (DualEM Inc, Canada).

500

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

510

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

520

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

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

530

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

537

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

543

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

572 susceptibility (for $\epsilon_r = 200$) on the top and with the effective relative permittivity (for $\kappa_{ph} = 50$
573 10-5 SI) on the bottom.

574

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

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

582

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

585

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

591

592 [Conflict of Interest and data availability statement](#)

593 Data sharing not applicable - no new data generated.

594

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658

659 Appendix A

660 Processing of EMI data

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

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

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

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

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

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

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

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

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

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

705 Knowing these slopes, it is possible to write:

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

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

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

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

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

733 In conclusion, if one of the two properties is dominant in the in-phase measurements, it would
734 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.