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6. ELECTRICAL SURVEYING

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In electrical methods, an electrical current is injected in the soil by means of a pair of electrodes. This current is either a d.c. current or a slow alternating current (several Hertz) to avoid polarization effects and eddy currents. The current flow in the whole volume of the soil and subsoil and its spatial distribution is a function of the spatial distribution of the electrical resistivities.

As the soil is rarely uniform, geophysicists use the term “apparent electrical resistivity” to name the “average” resistivity of the volume where the current can flow. This spatial distribution is measured by two or more electrodes on the ground surface, which measure the resulting voltage. The ratio of the voltage to the current, multiplied by a constant (the geometrical factor which takes into account the spatial position of the four electrodes) is the apparent electrical resistivity (r_a). The unit is “Ohm.m”. Because subsurface materials have generally different resistivities, measurements at the surface of the soil can characterize the vertical and horizontal distribution of underlying structures.

In Archaeology, typical resistivities range approximately from 40 Ohm.m – or even lower if clay content is higher–, to 300 Ohm.m. Resistivity of bedrock is higher in nearly all cases due to, broadly speaking, a lower amount of water. Would the soil be perfectly homogeneous and very deep, the apparent resistivity would be the true resistivity of the soil.

Generally, the geophysical data are interpreted as ‘anomalies’. This refers to the discrepancy between an ‘undisturbed’ environment with a uniform true resistivity and the observed apparent resistivity.

To a given distribution of structures corresponds a unique distribution of apparent resistivities. But the opposite is false: to a given set of data (apparent resistivity or conductivity, or any other geophysical parameter) can correspond different structures. This non-uniqueness of the inverse problem makes ER/EC distribution difficult to interpret. Consequently some additional data are often needed to characterize the anomalies.

COMPARISON TO EMI MEASUREMENTS

In EMI methods, a current is injected in the soil by means of low frequency variations of a magnetic field (H_p) originating from an oscillating current into a coil (antenna) above the soil. This magnetic field induces in the soil eddy currents (Faraday’s law) which spatial distribution is a function of the electrical conductivity (EC_a ,s_a) of the soil. The conductivity is the opposite of the electrical resistivity. Electrodes on the ground surface could measure these currents but, for EMI methods, they are measured by a second coil (Rx): the eddy currents generate a very small oscillating magnetic field (H_s). The Rx coils measures both the primary field (H_p) and the secondary field (H_s). What is measured on the Rx coil is a function of the different conductivities in the sub-soil but also of others factors like: orientation and distance between the two coils, operating frequency and magnetic susceptibility. Under specific constraints, named Low Induction Number (LIN), a simple direct expression can be found between apparent conductivities (s_a) and the ratio of the quadrature out of phase primary to secondary field (H_p / H_s). In this case, the measurement can be translated directly to conductivity and these instruments are often named conductivity meters. For archaeological purposes, we could be interested by the use of the in-phase component (proportional to magnetic susceptibility) and only a very few instruments are available on the market.

Using galvanic or electromagnetic induction instruments is a choice that is made by the geophysicist in the field. At this time, as a consequence of the limited choice of available instruments, EMI is not well developed for mapping archaeological structures at the contrary of DC methods. At the opposite, EMI is widely used for soil mapping or geomorphological investigations

We have found that the six main drawbacks of using EMI instruments are (Gebbers *et al.*, 2009):

– Time drift of the electronics that makes for example the merging of several maps acquired at different times very difficult,

– Mechanical drift of the instruments: any slight change of coil direction with respect one to each other results in a signal that can be as high as the one due to archaeological structures. Of course, when using towed systems, this problem becomes even more important,

– No absolute calibration: this is related to the first mentioned problem. Calibration of EM instruments is a very difficult problem. Normally obtaining a zero is done by raising the instrument (>2m) or making the calibration over a very resistive ground. Moreover the in-phase response (magnetic response) has also to be zeroed because of problems of phase mixing,

– Depth of investigation can be changed by coil orientation or coil separation but this is very limited in available instruments. Moreover, definition of depth of investigation is more difficult than in galvanic methods,

– Limited dynamic of measurements, especially for moderate and high resistivities (>200 Ohm.m).

– Limited time response: due to the low amplitude of the secondary magnetic field in the receiver coil, time integration has always to be performed in order to higher the signal to noise ratio. This integration makes the time response of these instruments very long, typically more than one second (time between the measurement of the ‘anomaly’ and the output measured signal). This is not important for hand-made instruments but becomes clearly a drawback for continuously towed systems.

Despite these drawbacks, we found two advantages of using EM instruments in the field that are:

– Simple instruments to operate in the field and that can be towed easily by an operator by hand and/or with a vehicle,

– Very good response over conductive soils (clay or salty soils for example).

To our experience, the drawbacks for using galvanic methods are:

– Contact resistance: when the soil is too dry, it is difficult and sometimes impossible to drive the current into the soil due to a too high contact resistance (>100Kohm for example),

– No measure possible when the soil is frozen (contact resistance + high resistivity of the ice),

– Workload heavier and longer than when using EMI instruments.

The advantages of using galvanic methods are:

– Many depths of investigation possible which are controlled mainly by the distance between current and injection electrodes,

– Absolute measurements (no calibration and no drift in the field),

– Wide dynamic of measurement (a few ohm.m to several ten thousands Ohm.m),

– Quick time response (a few milliseconds).

HISTORY OF ELECTRICAL MEASUREMENTS : MOVING TO CONTINUOUS MEASUREMENTS, THE ARP® SYSTEM

Considering the above mentioned drawbacks of galvanic methods, we have tried to overcome then by designing:

– a resistivimeter which can cope high contact resistance, have the best time response and easy to operate in the field,

– a mechanics that can be used as rolling electrodes and towed by an all-terrain vehicle even in very harsh environments,

– a hardware and software to drive the instruments, help the operator while driving (auto-guidance) and also makes a real time quality check of acquired parameters.

This system is named ARP© (Automated Electrical Profiling) and is patented (number 0101655, European extension pending). ARPÓ system is the result of a long history, which can be split in three steps:

1) The original prototype dates from the eighties. This proto was developed for the mapping of archaeological targets. This experimental system (Dabas *et al*., 1989) was named RATEAU (*Résistivimètre Autotracté à Enregistrement Automatique*: Automatic recording and self-towed resistivity meter). It was made of four modules namely:

– A square quadripole made with four rolling electrodes separated by 1 meter. Any type of all terrain vehicle (ATV) can tow this system (original speed was around 1m/s).

– A resistivimeter (RMCA4, CNRSÓ) that measures directly the electrical resistance. This specific resistivimeter tolerates very high contact resistance and is compatible with high-speed measurements (minimum 10 Hz).

– A computer that displays and stores the values of apparent electrical resistivities in real-time,

– A Doppler radar that triggers the ER measurements along the profiles at a fixed distance interval.

A tractor towed the system. The Center of Recherches Géophysiques de Garchy did the first application of RATEAU systems for Archaeology in the nineties with successful results published.

2) This system was further enhanced to 3 depths of investigation. The geometry of this new system named

Multi-depth Continuous Electrical Profiling: MuCEP (Panissod *et al*., 1997) was carefully designed by 3D simulations (forward modelling) in order to optimise the positioning of the electrodes on the ground surface versus depth information and also reduce the volume of the system which has to be packed in a "standard" van. The eight electrodes enable the ER to be measured for a depth of investigation approximately up to 0.5, 1 and 2 meters.

Meanwhile, at Wroxeter archaeological site, Dabas *et al*. showed that it was possible to survey continuously with a man-towed frame but also with a simple pole-pole configuration (Dabas, 2000). This experiment leads Geoscan Research (Bradford, England) to introduce a man-towed square quadripole using its standard RM15 resistivimeter (MSP 40 Mobile Sensor Platform).

3) The third system ARP © was developed specifically for agriculture by a spin-off from CNRS in 2001: Geocarta. Several improvements were made:

– Absolute positioning by RTK GPS,

– Possibility to acquire 3 measurements at a speed up to 6m/s with a spatial resolution of 10cm (area up to 1 ha by hour can now be surveyed in Archaeology),

– Development of a new resistivimeter for optimised synchronous measurement of 3 channels with a quick time response (44ms) and a high tolerance to contact resistance,

– Development of a chip for interfacing the different electronic boards,

– Development of real-time software on a ruggedized computer. Data are processed in real-time (both geographically and the 3 channel). Software evolved into a real-time GIS with auto-guiding possibilities and integration of other type of data (mainly satellite, orthophotos),

– Towing by a quad-bike.

In open-field areas, up to 10 ha can be surveyed in a day. In standard conditions, number of measurements in one hectare is around 300 000 (crossline spacing = 1m, in-line spacing = 10cm). The average velocity of data acquisition is around 4m/s.

There are now thirteen generations of ARP systems working in the field (Dabas, 2009). Compared to manual survey, the gain in terms of time of operation in the field was estimated to x20 at minimum.

In summary, we have found the following advantages of using the ARP:

– This system being towed by a quad bike, the damage to the crops is limited and this permits to survey areas over a wider temporal window in the year,

– If an RTK GPS is used, the very dense sampling of points enable to compute a very accurate Digital Elevation Model (DEM), which can be further used in the process of archaeological interpretation,

– Measurements being triggered by a radar Doppler at fixed intervals (10cm) means that whatever the variation of velocities while driving, the spatial sampling of measurements is uniform all over the field. Consequently the quality of the maps derived by interpolation is higher.

– Use of a GIS in the field with real-time quality check and auto-guidance means no topography previous to any field work, and thus only a single operator is needed.

– Areas up to 4 ha can be surveyed in a day.

METHODOLOGY- RESULTS-INTERPRETATION

DATA ACQUISITION: METHODOLOGY

The whole survey (2,33ha) has been done in one day by a single operator (11 May 2012 by Boris Pignède).

Despite a soil which began to be quite dry, the data obtained are very good. Current used was 5mA in order to get the highest tolerance to contact resistance (normally with a wet soil, current used is set to 10 or 20mA and this results in a better signal to noise ratio). Approximately 15% of data were discarded because of loss of electrical contact with the soil while moving (with a wet soil, this ratio can be lower than 1%).

The process of acquisition was done in 5hours and 33 minutes. The in-line spacing between each measurement was 4cm and cross-line spacing approximately 1meter. Cumulated length of profiles is 30 657m and average speed of acquisition was quite low (5.5 km/h) due to the dryness of this area. 20 123 GPS data points and 2 474 418 electrical measurements were acquired.

DATA PROCESSING

The data processing is done in four steps:

1- Translation of raw measurements into apparent electrical resistivities for the three depths of investigation (calibration), reprojection of the GPS points in local coordinates (UTM31) and assignment of a geographical position to each electrical measurement,

2- Despiking by using a moving average median filter (length=44cm, tolerance = 30%) along the profiles,

3- Gridding (2D interpolation) by using a bicubic spline operator. The resulting mesh is square (0,3m x 0,3m) and the points forms an image of 390 456 cells.

4- Displaying the grid in a GIS (Geocarta Office) for checking positional accuracy relative to other data and interpretation.

Due to problems with radio transmission of the RTK GPS in the field, most of the data were acquired in differential mode and not in RTK mode. Nevertheless, this problem did not resulted in a distorted electrical image because we were able to use many satellites (more than 17, taking into account the GLONASS configuration) and this has resulted in an estimated horizontal accuracy of 10cm (instead of 2cm with RTK).

A statistics of the gridded apparent resistivities (in Ohm.m) is displayed below:

	Channel1 (0 to 0,5m)	Channel2 (0 to 1m)	Channel3 (0 to 1.7m)
Number N	259 484	259 461	259 716
Mean	78.0	64.3	72.8
Median	74.3	61.3	69.8
First quartile	67.7	52.4	59.4
3rd quartile	86.7	72.3	82.2
1st-3rd quartile	19.0	19.9	22.8
Standard Deviation	19.8	17.7	19.9

RESULTS

We can see from the above table that the difference of resistivities between first and third quartile is very narrow. This means that the field is quite homogeneous globally at least down to 2meters.

Nevertheless, the mean apparent resistivity is lower for the 0 to 1meter interval than for the 0 to 0.5m and 0 to 2m interval. This means that the mean true resistivity is lower between 0.5 to 1m. This is probably due to higher water content for this intermediate range of depth. Deeper, the substratum is probably more resistive.

When looking more locally, linear parallel (N14°) and perpendicular (N104°) resistive structures appear nearly everywhere on the map (see fig XX). This orientation rotates anti-clockwise in the most southern part of the surveyed area. These structures are of course related to buried walls. A difference of minimum 20 Ohm.m up to 150 Ohm.m is observed in the apparent resistivities between the walls and the surrounding. This range and the fact that the surrounding is homogeneous as previously noticed, means that the walls can be clearly identified in the images.

Of course, as the walls are seen with ARP channel 1, this means that top of the walls are between 0 to 0,5m deep. When looking at ARP channel 2, some new walls not previously seen on ARP channel 1 appear in the North West of the surveyed area. This means that the top of the walls are deeper in this NW corner. The reason can be a higher destruction of the walls of course, but also a thicker soil cover in this area. The implication of this last point is important for archaeologists and for a strategy of preservation of the site. For the deepest map, the “doubling” of anomalies is a characteristic artifact generated by the equatorial dipole used (ARP channel 3) imaging superficial structures (more precisely, structures buried at a small depth compared to the distance between current and potential electrodes results in a doubling of the anomalies). Even if this is an artifact, this phenomenon can help in viewing the buried structures and we have found that archaeologists prefer this image in terms of interpretation.

All walls seem to delimitate small rooms with typical dimensions from 5 to 7m, except one single building of 42 by 20m. These dwellings are aligned along the main North “street” and the orthogonal “streets” (a mimimum of 10 can be seen). We can notice that electrical method do not see clearly these streets like in magnetic maps, but their presence is guessed from the orientation of the dwellings and a small ‘gap’ in the dwellings (channel 1 and 3 mainly). This shows clearly the complementarities between the different surveys.


1-a

1-b

1-c

1-d

Figure 1. Evolution of the systems for continuous measurement of electrical resistivities (1a : Rateau, 1b :MuCEP; 1c: ARP01©; 1d : ARP03 ©)

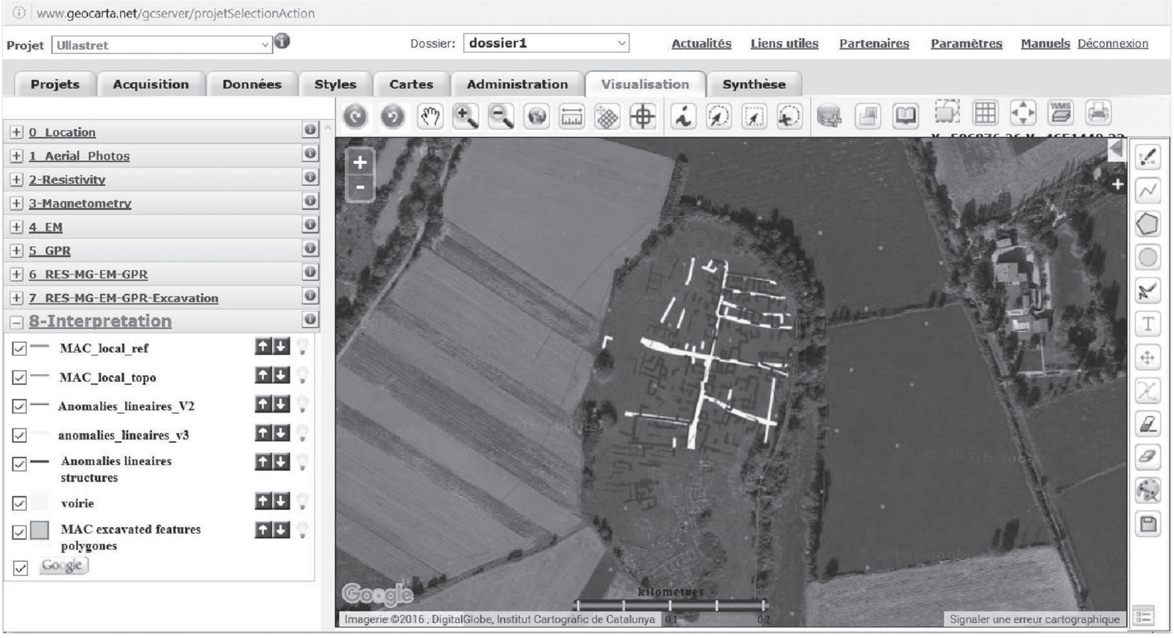

Figure 2. Copy of the web-GIS developed by Geocarta for the fieldwork of Ullastret

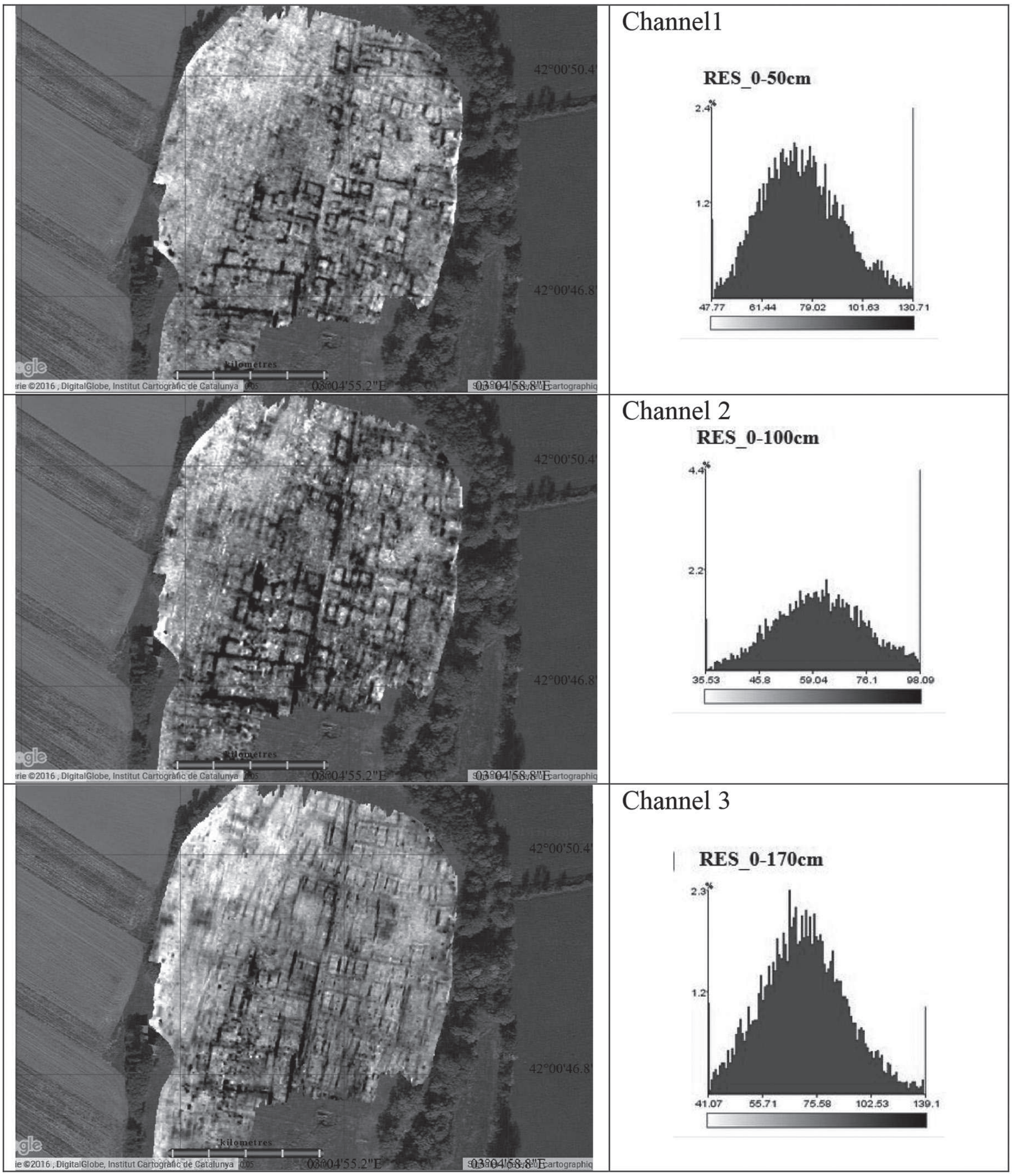

Figure 3. Apparent Electrical resistivities from ARP03© for the three depths of investigation and superposed with a aerial photos (copyright Google, DigitalGlobe and Institut Cartographic de Catalunya) (from up to bottom : 0 to 50cm; 0 to 1m and 0 to 1.7m)