ERT investigation of tumuli: does the errors in locating electrodes influence the resistivity?

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Abstract – **Among the princely tumuli near Vetulonia (Tuscany, Italy) the one of Poggio Pepe has never thoroughly been investigated. A joint project among three different departments of the University of Florence, lead to a new investigation campaign on this tumulus. The main goals are to verify the conservation structures state and to identify the tomb ancient access by means of geophysical methods. Moreover, this project aims to evaluate the influence on the geophysical acquired data of the error in collecting the geographical coordinates of the surface acquisition points. Optimizing the input data, in fact, it is possible to improve the anomalies localization and therefore facilitate the design of the excavation survey and the management of the research funding. The first results allow to make some assumptions about the state of the structures buried and suggest that in case of consistent error in locating acquisition points the measurement accuracy is strongly influenced.**

I. INTRODUCTION

During the 7th century BC, Vetulonia (Tuscany, Italy) was one of the most important cities in northern Etruria. Products of its handicraft cross the borders of Etruria and the Alps, demonstrating the economic power of the Vetulonian aristocracies. From the middle of the 7th century BC, the powerful princes of Vetulonia commissioned monumental tumuli that reach more then 90 metres in diameter and that are among the largest in the ancient world.

Between the end of 1800 and the beginning of 1900, Isidoro Falchi, the archaeologist to whom we owe the rediscovery of the ancient site of Vetulonia and its necropolises, investigated many of these funeral mounds (such as those of the Pietrera and Diavolino, in Tuscany) [1]. Tombs were built with large sandstone blocks, had a long access corridor (called *dromos*), and a quadrangular funeral chamber that was cover by a circular roof of protruding stone slabs. Nowadays, it is rare to find a tumulus with the roof still preserved. Moreover, the Pietrera tumulus has two funeral rooms that are placed one on each side of the *dromos* (Fig. 1a).
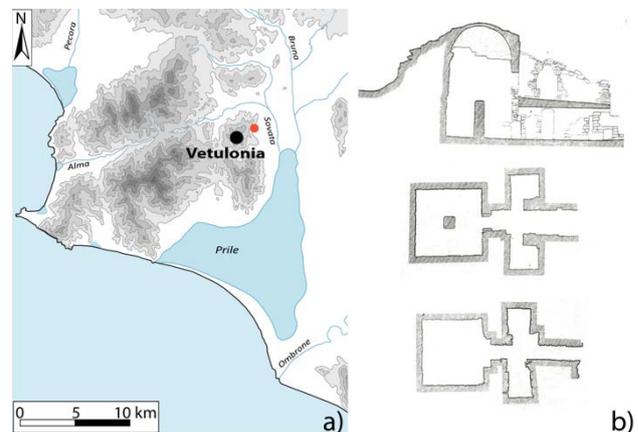

Fig. 1. a) Ancient map of the Etrurian region around Vetulonia in the 7th century BC. Red dot is the location of the Poggio Pepe Tumulus. b) vertical (on top) and horizontal (in the middle and on bottom) sections of the Pietrera tumulus.

Among the princely tumuli, the one of Poggio Pepe is located on the eastern side of the Vetulonia hill (red dot in Fig. 1) and overlooks the area in which the ancient Vetulonian port on the Prile lagoon was likely located. This mound has never thoroughly been investigated, even if,

between 1901 and 1910, Isidoro Falchi realised some excavation probes and brought to light the beginning of the *dromos* [2]. In this occasion, investigation showed that the tomb had already been ransacked and the archaeologist did not complete the excavation. Therefore, the internal structure of the Poggio Pepe tumulus is still unknown. Moreover, unlike other large tumuli, the Poggio Pepe one does not have a depression at the top, that usually is caused by the collapse of the funeral chamber cover. This could indicate that the inside of the chamber is still well preserved, with the roof intact.

The Etruscology Chair of the SAGAS Department of the University of Florence, that has been conducting research on the territory of Vetulonia for many years, has decided to undertake a new excavation campaign on the great tumulus of Poggio Pepe. The main aims are to verify the structures state of conservation and to identify the ancient access of the tomb. Given the goals of the project, the Chair started an ongoing project in collaboration with the Department of Earth Sciences (DST) of the University of Florence for an in-depth geophysical investigation of the tumulus. The geophysical investigation survey has been realised thanks to the authorization of the Soprintendenza Archeologia Belle Arti e Paesaggio for the Provinces of Arezzo, Siena and Grosseto

The exploration of tumuli is a challenging geophysical problem because of a) the complex distribution of the soil physical properties (i.e., 3D distribution of anomalies), b) the rough topography, and c) the size (sometimes of few meters) and burial depth of anthropogenic constructions (i.e., they are located within the first ten meters) [3-4]. Both 2D and 3D geoelectrical methods, like electrical resistivity tomographies (ERT), are increasingly popular. It can be easily seen that the final results resolution and accuracy depend on the spatial distribution of the acquisition points arranged on the surface (i.e., in the ERTs the distance among the electrodes and therefore the total length of the acquisition array) [5]. The precision in locating the acquisition points (i.e., the electrode position in the ERTs) plays a key role, too. Nevertheless, it is hard to find in literature papers that discuss about the influence on the final result of the errors in locating the acquisition point, while there are many papers about the influence on the result resolution of the surface spatial distribution of the acquisition points [3,5].

Therefore, one of the main goals of this work was to evaluate the influence on the ERT data acquired of the error in collecting electrode coordinates (GPS error). This kind of analysis has been conducted by the Department of Information Engineering (DINFO) of the University of Firenze. Moreover, along one ERT profile we collected data with different acquisition parameters (i.e., we changed the input voltage) to estimate their effect on the final result. Optimizing the input data, employed to reconstruct a reliable model of the subsoil, in fact, it is possible to improve the anomalies localization.

Consequently, this improvement facilitates the design of the excavation survey and allow to manage the research funding in a more efficient way, minimizing the archeological excavation survey costs.

In this paper we only present the first result of the analysis of the GPS error influence on the apparent resistivity data. Such an in-depth data check is an experiment that aims to evaluate the reliability of geophysical methods, for the investigation of structures buried at shallow depths, from a different/not common point of view.

II.   GEOPHYSICAL MEASUREMENTS

Starting from the '90s, electrical resistivity tomography (ERT) is a key technique for detecting near-surface anomalies from both geological and human origins. Therefore, it is widely and commonly used for archaeological purposes [6]. This method, by means of a complex relationship, allows to obtain the true ground resistivity distribution from apparent soil resistivity (ρ_a) measurements. Applying to the soil a DC current (I) through two electrodes (called *current electrodes*) and measuring the voltage (ΔV) generated in the ground through two different electrodes (called *voltage electrodes*) the apparent resistivity can be obtained as per the following eq. 1:

$$\rho_a = k \frac{\Delta V}{I} \qquad (1)$$

where k is the geometric factor [5]. Thus, the collected apparent resistivity is an indirect measurement of the soil property "electrical resistivity". Given the aim of the work it is important to recall here that k depends on the mutual distance among the four electrodes according to eq. 2:

$$k = \frac{2\pi}{\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)} = \frac{2\pi}{\left(\frac{1}{r_{AM}} - \frac{1}{r_{MB}} - \frac{1}{r_{AN}} + \frac{1}{r_{NB}}\right)} \qquad (2)$$

where r means the distance, A and B are the current electrodes, and M and N the voltage electrodes. Therefore, shorter the array length, smaller the k, and lower the penetration depth.

Four 2D-ERT (T1-T4 in Fig. 2) and one 3D-ERT C-shaped (C1 in Fig. 2) were carried out on Poggio Pepe tumuli during two different campaign. Given the aims of the work the theoretical electrodes space was set equal to 1.5 m in C1 and T1 (total linear length 106.5 m), and 1.0 m in T2-T4 (total length 71.0 m). T1 was collected to evaluate a) the hypothesis of the presence of the dromos and b) the maximum depth of the expected anomalies. C1 was performed to directly acquire 3D data in the area where we expect to find the dromos. The areal distribution of T2-T4 is according to the most recent literature that suggest that a radial distribution of the ERT is more suitable than a regular grid distribution [3]. Of course, to cover the whole tumulus surface and obtain a better 3D resolution it will be necessary to collect at least three more ERTs to fill in the empty area and/or other C- or O-shaped 3D-ERTs [7].
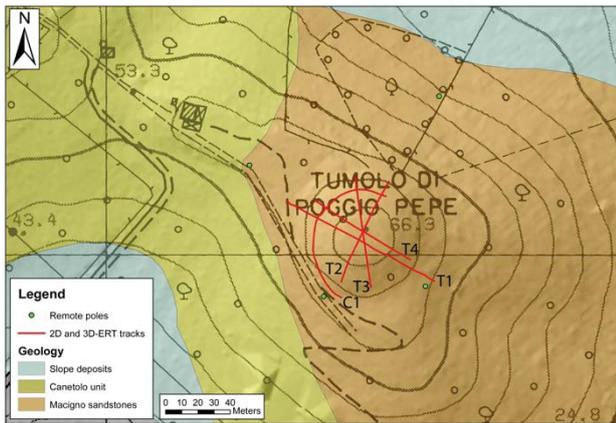
Fig. 2. Locations of the 2D-ERT (T1-T4, red lines) and 3D-ERT (C1, C-shaped red line) over the geological map of the area. Light green dots are the remote poles employed in the pole-dipole acquisitions.

An Iris SyscalPro 48 electrodes (10-channels receiver), joined with a 24-electrode external link (for a total of 72 electrodes), were used to collect all the data. All the electrodes were georeferred using a Leica 1200 differential GPS in Real Time Kinematic mode. The GPS acceptable acquisition error was set equal to 0.05 m, i.e., the instrument asks the operator before to store data with a higher error. Unfortunately, because of a non-favorable satellite geometry and a low quality of the transmission signal, only the 11.0% of the T1 data were stored with an error lower than 0.05 m, and among this only the 2.8% has an error lower than 0.03 m. For the other survey the percentage of data with an error lower than 0.05 m and 0.03 m is 75.0% and 57.5% for C1, 82.0% and 66.7% for T2, 94.5% and 74.0% for T3, 96.0% and 77.0% for T4, respectively.

Two different arrays were employed to collect data: i) the dipole–dipole array, based on current and voltage cables widely separated to enhance the lateral resolutions at shallow depths and to minimise electromagnetic inductive noise; and ii) the pole-dipole array, that combines consistent signal strength with a high resolution and large depth of investigation [3,5].

The commercial software ErtLab[TM] was used to invert the ERT data [8]. Starting from a homogeneous half-space, it employs the finite-element discretisation and it models the true remote electrode position (i.e., for pole-dipole array it takes into account the effects of the remote pole when it is not placed at an appropriate "infinite" distance from the voltage dipole). The software also implements an optimal data noise management (i.e., the error that affects the field data) and finally, it calculates the quality of an inversion minimizing the misfit function between the field and modelled data [9]. Given the good quality of the acquired data, the "data noise error" was set equal to 1% for each ERT and the starting apparent resistivity was chosen equal to 170 Ωm.

Fig. 3 shows the results of each ERT. It is possible to

note that the soil in the study area has a resistivity value lower than 250 Ωm (blue colours), that is typical for sandstone. According to the geological map (Fig. 2), in fact, in the study area there are sandstone belonging to the Macigno Unit (dated back to the Upper Oligocene/Lower Miocene) and shales and limestones belonging to the Canetolo Unit (dated back to the Paleocene/Eocene). It is also possible to note that within the first 10 m there are some high resistivity anomalies (values higher than 500 Ωm associated to green and red colours), that can be associated to the rocky blocks used to build the anthropic structures. In particular, the anomalys A in 2D-ERT_T1 (Fig. 3a) and 2D-ERT_T3 (Fig. 3c), because their elongated shape, can be associated to the *dromos* or to its shadow, if the ERTs profiles do not cross it. Anomalies B in 2D-ERT_T2 (Fig. 3b), 2D-ERT_T3 (Fig. 3c) and 2D-ERT_T4 (Fig. 3d) can be associated to the chamber filled whether with soil or air. In particular the high resistivity anomalies highlighted with b, can be associated to the walls of the chamber. If the hypothesis that the roof of this chamber is still intact, then the high resistivity anomaly C in 2D-ERT_T2 (Fig. 3b) can be associate to a lateral tomb, very common in this kind of tumuli. Otherwise, this anomaly can be generated by the stone slabs removed from the roof.
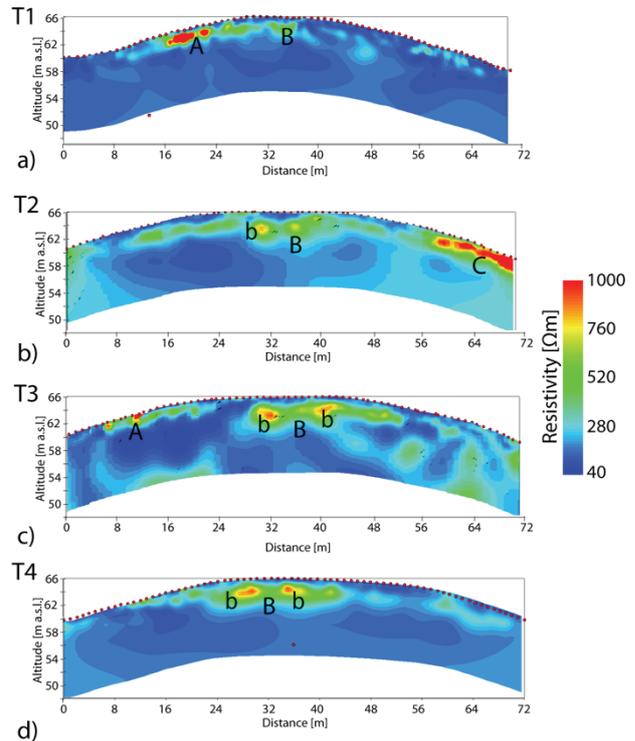

Fig. 3. The electrical models of the subsoil for the 2D-ERTs (T1-T4 from the top to the bottom).

A 3D view of the results is shown in Fig. 4: the volume in the middle and highlighted in green (B) can be associate to the chamber, while the volume C to the lateral tomb. Fig. 5 shows a slice of the investigated volume: from this

view it is clear that the high resistivity in the middle is not uniform, so the anomalies b can be interpreted as the chamber walls.
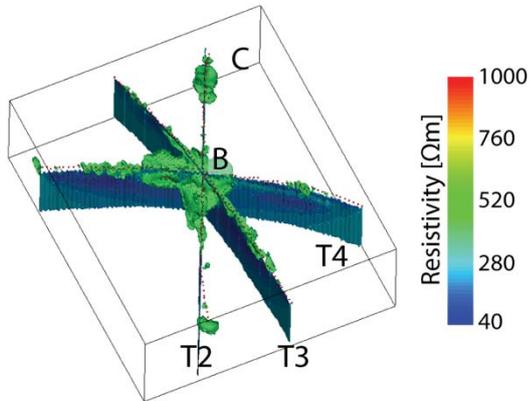

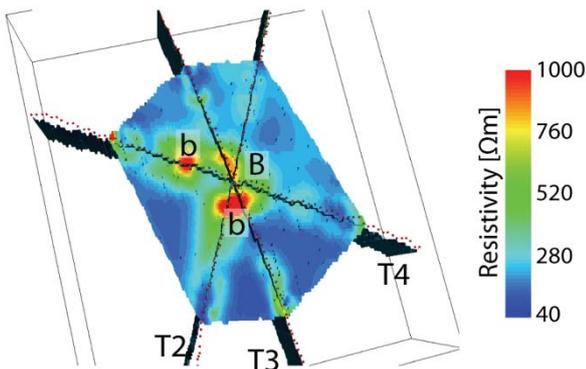*Fig. 4. Locations of the 2D-ERT (T1-T4) and 3D-ERT (C1).*

Fig. 5. Locations of the 2D-ERT (T1-T4) and 3D-ERT (C1).

III.   CRITICAL DATA ANALYSIS

This section focuses on the quality of the input data for the inversion algorithm. In particular, the aim of this procedure is to evaluate how the uncertainty of the electrode location affects the indirect measurement of the apparent resistivity.

One of the main issues of this type of measurement campaign is the deployment of the electrodes carried out with a GPS localization system. The localization is deeply influenced by the satellites geometry, the quality of the transmission signal, and the presence of obstacles for the transmission, such as trees, buildings, mountains, etc. [10] The measurement set-up is bounded to the instruments and the applications. Therefore, this procedure is based on Monte Carlo simulation (MCS) to consider the error in the positioning of the electrodes caused by the GPS. MCS is basically defined as a problem-solving technique used to gate the probability approximation of certain results by running multiple trial runs, called simulations, relying on variables randomly selected [11-13]. The statistical characteristics of the experiments (model outputs) are observed, and conclusions on the model outputs are drawn [14].

The procedure for the data analysis follows this scheme:
1. acquire input data (voltages, currents, location of electrodes);
2. construct a domain of possible location of electrodes, considering the uncertainty given by the GPS;
3. set i=1 and N=number of MC sample;
4. generate random inputs over the domain according to a probability distribution (uniform and normal);
5. calculate the geometric factor and the apparent resistivity;
6. if any sample left then return to step 3 else continue to step 7;
7. collect final results.

As well-known, the continuous uniform distribution is a symmetric probability distribution in which all the values in the distribution interval are equally probable. The range is defined by the minimum and maximum of the possible location point [15]. The normal distribution (or Gaussian distribution) is a continuous probability distribution with single central peak at the mean value; the shape of the curve is described as a bell-shaped with the graph falling off evenly on either side of the mean [15].

Figure 6 shows an example of the two distributions (uniform and normal) chosen for one possible location of the electrode A. Both have the same mean, the uncertainty of the points is used to calculate the parameters of the distributions. Considering A the measurement point (see Fig. 6) and ε the uncertainty provided by the GPS related to that point, for the uniform distribution the admissible range of value is [A-0.5ε, A+0.5ε], while the normal distribution is calculated taking into account that $3\sigma = 0.5\varepsilon$ (i.e., the 99.73% of values lie within the same range used for the uniform distribution) where σ is the standard deviation.
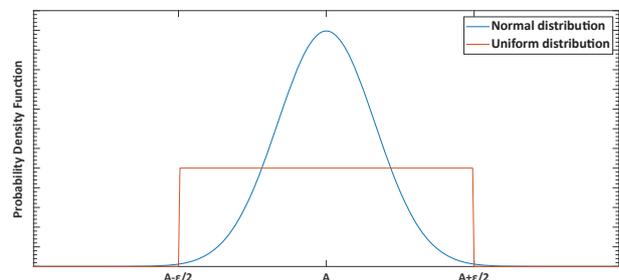

Fig. 6. Example of uniform and normal distribution used to model data.

This preliminary analysis considers only the T1 acquisitions (that with the highest GPS error), which contains 72 possible location of the electrodes deployed in

a linear range of 106.5 m; resulting in 2475 values of apparent resistivity. For each one of them, 10000 samples are generated.

Fig. 7 shows the results of MCS obtained using both uniform and normal distribution for a single measurement point. The two histograms in the figure (uniform distribution in brown and normal distribution in blue) highlight the great variability of the resistivity when the localization of the electrodes is affected by error. The range of resistivity related to the uniform distribution is larger than the normal. The normal distribution maintains its bell-shape and its range is quite limited. The black dotted line is the apparent resistivity measured by the instrument, the green stands for the mean of the normal distribution and the red for the uniform distribution. The other statistical parameters are included in Table 1.
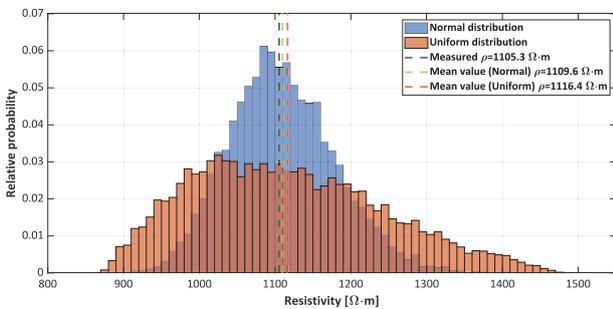

Fig. 7. Histograms of the MC outputs for a single acquisition considering both uniform and normal distribution.

Table 1. Statistical parameter of the distributions.

Statistical parameters	Normal distribution	Uniform distribution
Mean	1109.6 Ωm	1116.4 Ωm
Median	1105.3 Ωm	1104.3 Ωm
25th Percentile	1060.4 Ωm	1018.7 Ωm
75th Percentile	1154.5 Ωm	1202.1 Ωm

Fig. 8 illustrates the measured and simulated resistivity (on the left column) and the relative error for each acquisition (on the right column). The two subplots on the top of the figure refers to the uniform distribution while the other two to the normal distribution. The acquisitions are sorted from the minimum to the maximum length of the dipole-dipole. Therefore, the higher is the number of acquisition and deeper is the measured point. Both analyses agree that increasing the array length and consequently investigating deeper points, the relative error, between measured and simulated result, decreases. So, the influence of the uncertainty on the electrode localization is relevant only for surface investigations, and it becomes negligible for deeper analysis.

Analyzing the two subplots on the right side of Fig. 8, it is possible to note that both have the same trend of the relative error, but the normal distribution is characterized by an average error approximately three times lower than the uniform distribution. Overall, these results suggest that the normal distribution is more suitable to approximate this type of uncertain data.
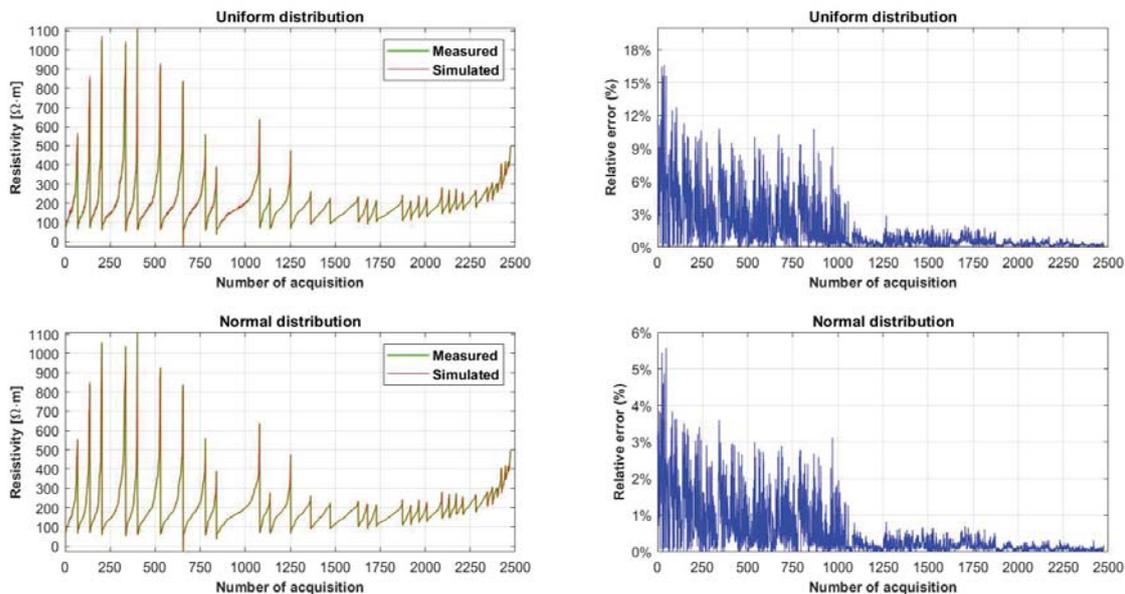

Fig. 8. Comparison between measured and MC simulated resistivity and their relative error with uniform and normal distributions.

IV. DISCUSSION AND CONCLUSION

The results of the geophysical investigation allow to make some assumptions about the state of the structures buried under the mound of Poggio Pepe. In fact, the surveys identified remains of the wall that originally surrounded the great tumulus, and intercepted radial surface structures that have been interpreted as the highest part of the sidewalls of the tomb access corridor. Moreover, various radial tomographies made it possible to recognize an anomaly that represents the walls of the funeral chamber and to estimate its size, between 3 m and 4 m per side. Further development of the investigation and data analysis will allow a greater definition of the internal structures and particular attention will be given to the state of the tomb roof. Its conservation status is of great importance for the excavation strategy: in fact, if research will ascertain that the roof is still preserved, the excavation of the funeral chamber will start from the corridor and appropriate works will have to be planned to support the central cover; on the contrary, if the roof collapsed, excavation will begin from the top of the mound.

The results of the preliminary analysis of the influence on the apparent resistivity data of the GPS error suggest that in case of consistent GPS uncertainty, caused by physical and atmospheric conditions, the shallow apparent resistivity is strongly influenced by a wrong deployment of electrodes. Therefore, in case of archeological application, where the area of interest is limited to the first meters underground, the measurement campaign should be rescheduled another day (with different conditions). That leads to an optimization of input data and consequently to an optimization of the localization of the archeological target, with a minimization of cost.

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