

# EMI data from an archaeological resistive target revisited

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## ABSTRACT

In a previous work, we presented the analysis and interpretation of geophysical data acquired at the Floridablanca archaeological site in Patagonia, Argentina. The electromagnetic induction method (EMI) was used to detect and localize the anomalous zone of interest quickly. Afterwards, a quantitative characterization of the structure responsible for this anomaly was achieved by inverting geoelectrical data.

In this work, we re-analyse the EMI data to discover whether it could also provide us with quantitative information about our target, which exhibits a resistive signature with respect to the host medium. First, an alternative visualization of the data is carried out; this allows us to detect some features of the anomaly that could not be distinguished before. It also makes clear which of the configurations used in the data acquisition exhibits the best sensitivity and resolution. The EMI data corresponding to the anomalous zone are then adjusted with a trial-and-error procedure, using a 2D forward modelling method based on a Raleigh–Fourier approach. The response of two adobe walls with a tile deposit in between them is calculated and the resulting model shows good agreement with the model obtained from the inversion of the geoelectrical data. Also, the synthetic response of two adobe walls without the tile deposit is calculated; we find that this response is different and the data cannot be adjusted with this model. We conclude that the EMI method is appropriate for discriminating different types of resistive structure and that it can be used to obtain quantitative information when 2D modelling is performed.

## INTRODUCTION

Since 2000, we have been carrying out geophysical studies to characterize the Floridablanca archaeological site. This 18th century site is located in San Julian Bay, Santa Cruz Province, Argentina ( $49^{\circ} 16' 38''\text{S}$ ,  $67^{\circ} 51' 22''\text{W}$ ) and corresponds to a small village established as a part of a Spanish Crown project for the colonization and defence of the Patagonian Atlantic coast. The site has an area of  $10\,000\text{ m}^2$  and the topography proved to be associated with buried archaeological structures. The changes in elevation across the area define the different sectors of the site, which are marked with black rectangles in Fig. 1. Archaeological excavations showed the presence of different types of adobe structure. The presence of ceramic tiles inside some of these structures was attributed to a roof collapse (Senatore *et al.* 2000). The presence of tiles in a sector indicates that the structure was completed and that people probably dwelt there. Excavations of these structures can provide the archaeological community with valuable information about the history of the site and the people who occupied it. A preliminary geophysical study carried out in another sector of the site indicated that the adobe walls and the roof collapse appear in the data as resistive anomalies with

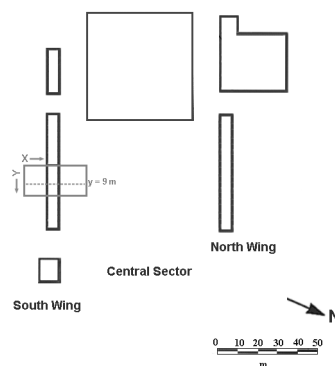


FIGURE 1  
Map of the Floridablanca archaeological site. The black rectangles indicate the different sectors of the site and the grey rectangle is the surveyed area.

respect to the host medium, and that the tiles are more resistive than the adobe walls (Lascano *et al.* 2003).

We applied electromagnetic induction (EMI) and geoelectrical methods to survey the site. The traditional geoelectric method is very reliable for mapping electrical resistivity contrasts and provides high-resolution electrical images, even when mapping 3D structures. However, it is not as practical as the EMI method when the survey area is large and high lateral resolution is required for shallow prospecting. In these cases, a better strategy is first to apply an alternative method, such as ground-penetrating radar (GPR) or EMI, to delimit the anomalous zones of inter-

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FIGURE 2

Photograph of the site showing the landscape elevation that defines the South Wing sector. The small bushes would make a GPR survey very difficult.

est (Chamberlain *et al.* 2000; Huang and Won 2004), and then use the geoelectrical method to get a local electrical image of the subsoil. In our study zone, the presence of dense vegetation made the EMI method especially appropriate because it does not require direct contact with the soil. Figure 2 shows a photograph of the field site, where the short bushes that form this dense vegetation and a sector of the study zone can be seen. We used an EMI system to detect and localize the anomalous zones and then the geoelectric method to obtain an electrical image of the subsoil. Osella *et al.* (2004) showed results of the previous work. These results were confirmed by archaeological excavations.

The EMI method can be used to survey an area very quickly, so it would be helpful if it could be used not only to detect anomalous zones but also to obtain the electrical characterization of the structure of interest. This encouraged us to carry out a more substantial analysis of the EMI data available, to investigate whether the presence of adobe walls and a roof collapse could be quantitatively characterized.

### DATA ANALYSIS

EMI data were acquired using the multifrequency electromagnetic profiler GEM-300 (Won *et al.* 1996), covering an area of approximately 400 m<sup>2</sup>, which is marked with a grey rectangle in Fig. 1. The profiles were orientated along the *x*-axis (see Fig. 1) with stations every 1 m. In total, 15 lines with 1-m separation were collected. A frequency range from 330 to 19 325 Hz was used with four different configurations. Dipole axes were parallel to the ground in configurations H1 and H2, and perpendicular to it in configurations V1 and V2; the instrument axis was coincident with the profile line in configurations V1 and H1, and perpendicular to it in configurations V2 and H2. It is important to note that the survey lines were perpendicular to the symmetry axis (the *y*-axis) of the underground structure under study.

The first step in the revision of our EMI data is to evaluate which is the best way to visualize them. Usually, plan-view maps

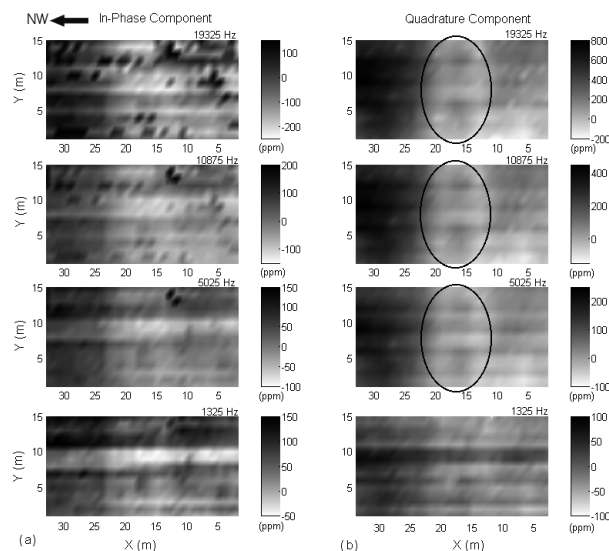


FIGURE 3

(a) In-phase and (b) quadrature components, in ppm, for the H2 configuration at four frequencies. The ellipses indicate the location of the resistive anomalies (from Osella *et al.* 2004).

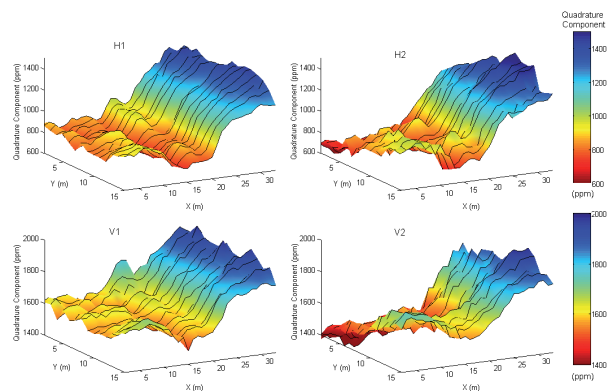


FIGURE 4

3D visualization of the quadrature component of the EMI data for all the profiles for configurations, H1, H2, V1 and V2.

are made with different frequencies for the in-phase and quadrature components of the data. As an example, in Fig. 3 we reproduce the original plan-view maps of the H2 data shown by Osella *et al.* (2004). We found that a 3D graphical visualization of the lines for a specific frequency is superior to the plan views. In our case, the target has a resistive signature and exhibits a small anomaly compared with that produced by conductive bodies; hence the 3D visualization shows some important details of the data that remained unseen in the plan views. Because we are dealing with resistive targets, the in-phase component does not give us any significant information and so we show only the quadrature component of the data. Also, we show only the highest frequency because the behaviour is similar for all frequencies, except that the amplitude becomes smaller as the frequency

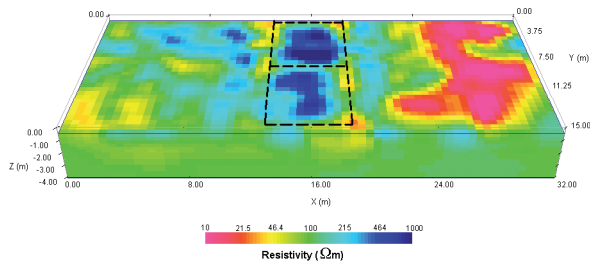


FIGURE 5

3D inversion results of the geoelectric data from the surveyed area. The dashed lines indicate the presence of the adobe walls with a tile deposit between them.

decreases. The 3D visualization is shown in Fig. 4 for all the configurations used at a frequency of 19325 Hz.

The lowest values of the quadrature component are centred at approximately 15 m and can be distinguished clearly in configurations H1 and H2. Configuration V1 is noisier but the same behaviour can still be clearly seen, while in configuration V2 this feature has almost disappeared. These low values are located at the elevation of the sector of the study site, and correspond to a resistive buried body associated with a roof collapse scattered in between two adobe walls. Although this anomaly was described in our previous work (Osella *et al.* 2004), it is far clearer in these graphics than in the plan-view maps shown before. The anomaly centred at 15 m is not large and its fine features could not be distinguished in a plan view. Also, the difference in behaviour between all the configurations is now evident. It is important to note that there is a particular feature of configuration H2 that is not present in the other configurations. In the H2 configuration, all the lines behave in the same way except for two, i.e. the lines carried out along  $y = 6$  m and  $y = 12$  m, for which higher values are found between approximately  $x = 13$  m and  $x = 18$  m. These higher values can be associated with two internal walls located along the  $x$ -axis. These walls, as it will be shown below, also appeared in the geoelectrical inversion. This particular behaviour of configuration H2 was not observed in a plan-view map. Thus, configuration H2 is found to be the only one with sufficient sensitivity to detect these walls.

Geoelectrical data were acquired using the multi-electrode resistivity meter Saris 500. We deployed dipole-dipole arrays with apertures of 0.5 m along lines coincident with some of the EMI profiles. In order to obtain the electrical images, data were inverted by applying the DCIP3D inversion code based on the work of Oldenburg *et al.* (1993) and Oldenburg and Li (1994). The 3D inversion of these profiles is shown in Fig. 5 (from Osella *et al.* 2004). In this figure, the most resistive zone corresponds to a tile deposit and dashed lines mark the limits of the anomalous zone where the archaeological structure was expected to be found. More localized 2D and 3D geoelectrical inversions indicated that the internal walls were at approximately  $y = 7$  m and  $y = 13$  m, i.e. shifted 1 m from the positions indicated by the

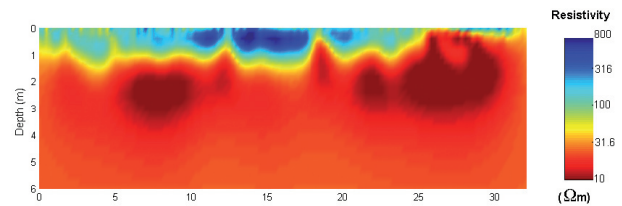


FIGURE 6

Structure of the subsurface below the profile studied (coincident with EMI line corresponding to  $y = 9$  m), obtained by 2D inversion of geoelectrical data.

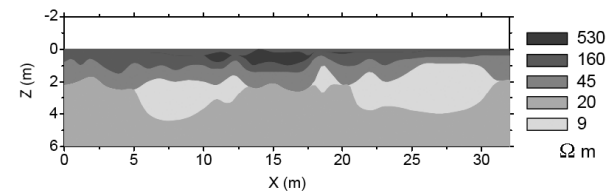


FIGURE 7

Multilayer synthetic model (Model A) of the subsurface below the profile  $y = 9$  m.

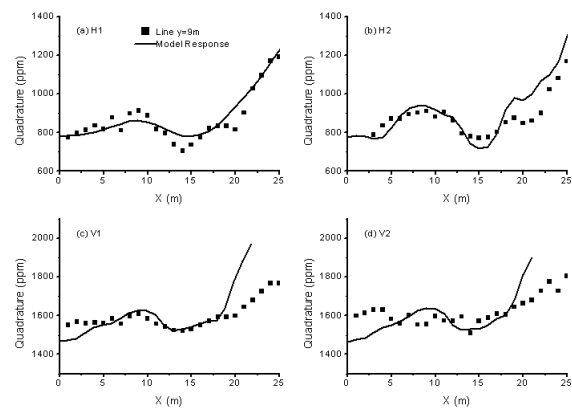


FIGURE 8

Synthetic quadrature responses of the model shown in Fig. 7, calculated at 19 325 Hz, for the four configurations together with the corresponding field data acquired along this line. To show the anomalous zone clearly we show only the first 26 m of the profile.

H2 data. The agreement between both results is quite good, taking into account the fact that the EMI equipment is 1.67 m long.

## MODELLING A SELECTED PROFILE

We performed 2D modelling of EMI data corresponding to one of the profiles studied. We employed a trial-and-error procedure using a 2D forward modelling method, presented in a previous work (Martinelli *et al.* 2004) and based on a Rayleigh–Fourier approach, which is an alternative to the 2D finite-difference and finite-element methods available. This technique is especially

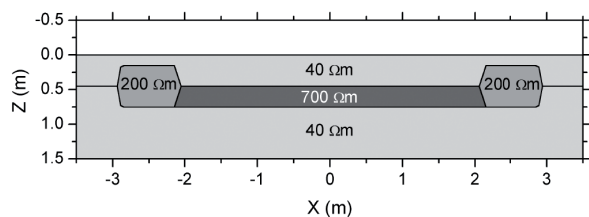


FIGURE 9

Schematic model representing the buried archaeological structure (Model B). The 200- $\Omega\text{m}$  bodies correspond to the adobe walls and the 700- $\Omega\text{m}$  body corresponds to the tile deposit.

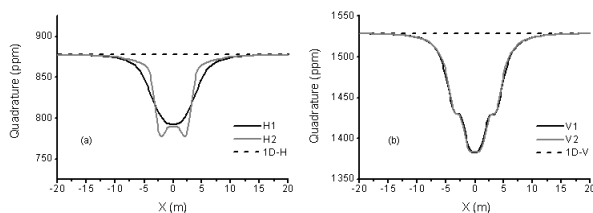


FIGURE 10

Synthetic quadrature responses of Model B, calculated at 19 325 Hz, for the four configurations together with the corresponding 1D responses of the host medium for the horizontal and vertical configurations, 1D-H and 1D-V, respectively.

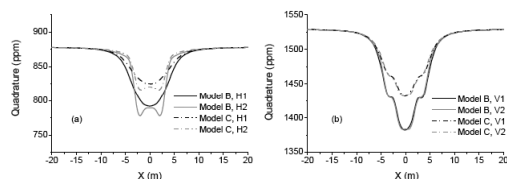


FIGURE 11

Synthetic quadrature responses of Model C, which is the same as Model B but with the archaeological structure situated 0.4 m deeper, calculated at 19 325 Hz, for the four configurations, together with the corresponding responses of Model B.

suitable for modelling multilayered structures with irregular boundaries.

We selected data acquired along the profile  $y = 9$  m (Fig. 1). This profile crosses the external adobe walls and the tile deposit and coincides with one of the geoelectric profile lines. Furthermore, it lies in the middle of the two profiles influenced by the internal walls in configuration H2. Figure 6 shows the 2D geoelectric image corresponding to this profile. We used this image to design the starting multilayered model for the adjustment. Figure 7 shows the final model (Model A). The synthetic quadrature responses of Model A, calculated using our code for the four configurations previously described, are compared in Fig. 8 with the corresponding field data for a frequency of 19 325 Hz. We show only the quadrature components because only they are sensitive to the target.

As we use simplified models of the subsurface and a trial-

and-error procedure, it is not expected that our synthetic responses could reproduce the finest details of the anomalies observed in the EMI data. Nevertheless, they should follow their general behaviour. As it can be seen in Fig. 8, this occurs for the H1, H2 and V1 configurations for values of  $x$  between approximately 4 and 18 m. Clearly, there is no agreement between the synthetic V2 responses and the corresponding data, but as we previously commented, these data were the noisiest. In cases V1 and V2, the responses for  $x > 18$  m are greatly overestimated. This may be attributed to an overestimate of the actual conductivity at depth in the geoelectric model. It appears that, in that zone, configurations V1 and V2 have a penetration depth greater than in geoelectric data and they detect the base of the more conductive layer. Configurations H1 and H2 have less penetration; this data can be adjusted using Model A.

### MODELLING THE LOCALIZED TARGET: TWO ADOBE WALLS WITH A TILE DEPOSIT BETWEEN THEM

To determine whether EMI quadrature responses can be used not only to detect but also to characterize the localized target, we designed a simplified 2D model of the target and calculated its synthetic response using our 2D forward modelling code. The geometry of this model is defined according to the findings of the excavations. The initial resistivities are selected taking into account the results of the 2D geoelectrical inversion shown in Fig. 6. The resistivity values are varied using a trial-and-error procedure until the magnitudes of the anomalies in the synthetic quadrature components H1, H2 and V1 are similar to those observed in the corresponding data. We consider only these configurations because configuration V2 did not detect the target, as can be appreciated from Fig. 8. Figure 9 shows the final model (Model B). The 200- $\Omega\text{m}$  resistivity bodies correspond to the adobe walls and the 700- $\Omega\text{m}$  resistivity body represents the collapsed roof, composed mainly of tiles. Figure 10 shows the synthetic quadrature responses of this model calculated at 19 325 Hz, respectively, for the four configurations. These results are compared to the actual behaviour of data in the zone over the target (Figs 5 and 6). The structure of the subsurface below the profile studied is not as simple as in this schematic model where the host medium is uniform. Nevertheless, not only the magnitudes but also the widths of the anomalies observed in data in the components H1, H2, and V1 are reproduced approximately. According to the theoretical modelling, V2 data exhibit resistive anomalies similar to those found for the V1 configuration, but these anomalies were not detected. This misdetection may be caused by a 3D effect due to the fact that in this configuration the instrument axis is perpendicular to the transverse walls. This is also the case for H2, but this configuration has a lower depth penetration than V2.

From the analysis of the synthetic results, we can draw some conclusions. The anomalies in the quadrature components produced by Model B for all the configurations have similar magni-



tudes and are clearly detectable, although they are smaller than those produced by conductive bodies. The lateral extension of the anomalies in the H2 configuration gives the best estimate of the width of the structure. Finally, for completeness we mention that in-phase responses differ from the corresponding responses of a 40- $\Omega\text{m}$  half-space by less than 1.7% for the V1, V2 and H1 configurations, and by less than 3.8% for H2.

To demonstrate the sensitivity of the response with respect to the depth of the archaeological structure, we increased its depth by 0.4 m, leaving the rest of the parameters unchanged (Model C). The response of Model C together with the response of Model B at 19 325 Hz, is shown in Fig. 11. The two responses can be differentiated, since the differences in the amplitudes of the anomalies are greater than the uncertainty of the measurements.

### MODELLING TWO ADOBE WALLS WITHOUT A TILE DEPOSIT

Excavations revealed that in other zones of the site, there are remains of adobe walls without tile deposits. Therefore, we investigated the conditions under which these structures can be detected by the EMI method and if their responses could be differentiated from those of Model B. Moreover, the presence or absence of a roof collapse is an important issue in determining whether a structure was inhabited. First, we built a new model (Model D) by removing the 700- $\Omega\text{m}$  body from the model shown in Fig. 9, leaving the rest of the parameters unchanged. Once more, we calculated the synthetic responses of this model for the four configurations. The quadrature components at 19 325 Hz are shown in

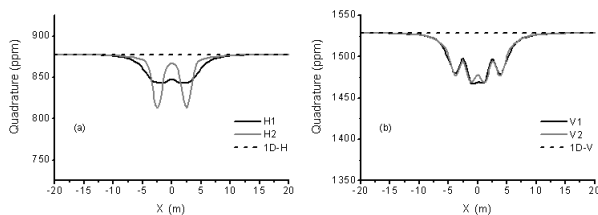


FIGURE 12 Synthetic quadrature responses obtained after removing the 700- $\Omega\text{m}$  body from Model B (Model D), at 19 325 Hz, for the four configurations, together with the corresponding 1D responses of the host medium (dashed lines).

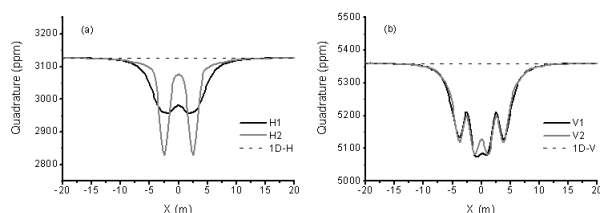


FIGURE 13 Synthetic quadrature components of a structure similar to Model D, but with a host medium of 10- $\Omega\text{m}$  resistivity at 19 325 Hz. The corresponding 1D responses of the host medium are also shown (dashed lines).

Fig. 12. The lowest anomaly corresponds to the H1 configuration while the H2 configuration clearly has the best resolving power. Comparing Figs 10 and 12, it can be seen that the anomaly in each configuration is smaller for Model D. Therefore, we can conclude that for the same host medium, it is more difficult to detect adobe walls alone. Nevertheless, the chance of detecting the walls improves greatly as the resistivity of the host medium decreases. Figure 13 shows the quadrature components calculated at 19 325 Hz for the same structure as in Model D but embedded in a 10- $\Omega\text{m}$  resistivity host (Model E). In this case, the adobe walls are clearly detectable.

### CONCLUSIONS

The EMI data obtained at the Floridablanca archaeological site were revisited to study how the interpretation could be enhanced beyond the mere detection of anomalies. Our objective was to use this data to characterize the resistive structures present at the site.

Using alternative plan-view contour maps to visualize the data, we found that we could identify some small anomalies that could not be detected before. We found that configurations H1 and H2 detected our resistive target (two adobe walls with a tile deposit in between) most clearly. Configuration H2 was the most sensitive as it detected structures that the rest of the configurations did not.

The response corresponding to the structure of interest was analysed using a 2D forward model of a schematic of the two adobe walls and the tile deposit. The parameters of the model were varied until the responses corresponded to the data. The model presented was in good agreement with the results obtained with the geoelectric inversion results, achieving a good characterization of our target.

In the same way, two adobe walls without the tile deposit were modelled, and we found that the response was very different from the former case. The synthetic responses also showed that configuration H2 had the best resolution. This was especially evident in the case of the model without tiles. Hence, we confirmed that the EMI method is sufficiently sensitive to discriminate between different types of resistive structure, such as those found in our study zone. These results reinforce the theory that the EMI method is suitable to define the electrical structure of resistive targets provided 2D modelling techniques are applied.

### ACKNOWLEDGEMENTS

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