<table>
<tr><td colspan="4">MANUSCRIT ACCEPTAT</td><td rowspan="3"></td></tr>
<tr><td colspan="4">Archaeological excavation confirms the geophysical anomalies recorded at the Cathedral of Tarragona: a comparative study</td></tr>
<tr><td colspan="4">A. Casas ; P.L. Cosentino ; E. García ; M. Himi ; J.Mª Macías ; R. Martorana ; A. Muñoz ; I. Teixell ; R. Sala</td></tr>
<tr><td>Publicació</td><td colspan="4">Near Surface 2011 - 17th EAGE European Meeting of Environmental and Engineering Geophysics</td></tr>
<tr><td>DOI</td><td colspan="4">http://dx.doi.org/10.3997/2214-4609.20144481</td></tr>
<tr><td>Disponible en línia</td><td></td><td>Data de publicació</td><td colspan="2">12/11/2011</td></tr>
<tr><td colspan="5">Per citar aquest document:

Casas, A., Cosentino, P. L., Garcia, E., Himi, M., Macias, J. M., Martorana, R., Sala, R., Muñoz, A., (2011) «Archaeological Excavation Confirms the Geophysical Anomalies Recorded at the Cathedral of Tarragona -A Comparative Study» Near Surface 2011 - 17th European Meeting of Environmental and Engineering Geophysics</td></tr>
<tr><td colspan="5">Aquest arxiu PDF conté el manuscrit acceptat per a la seva publicació.</td></tr>
</table>

Abstract

An integrated geophysical survey was conducted in September 2007 at the Cathedral of Tarragona (Catalonia, NE Spain), to search for archaeological remains of the Roman temple dedicated to the Emperor Augustus. Many hypotheses about its location have been put forward, the most recent ones suggesting it could be inside the present cathedral. Tarragona's Cathedral, one of the most famous churches in Spain (12th century), was built during the evolution from the Romanesque to Gothic styles. As its area is rather wide, direct digging to detect hidden structures would be expensive and also interfere with religious services. Consequently, the use of detailed noninvasive analyses was preferred. A project including Electrical resistivity tomography (ERT) and Ground probing radar (GPR) was planned for a year and conducted during a week of intensive field survey. Both ERT and GPR provided detailed information about subsoil structures.

Different ERT techniques and arrays were used, ranging from standard WennerSchlumberger 2D sections to full 3D electrical imaging using the MYG array. Electrical resistivity data were recorded extensively, making available many thousands of apparent resistivity points to obtain a complete 3D image after full inversion. The geophysical results were clear enough to persuade the archaeologists to excavate the area. The excavation confirmed the geophysical interpretation.

In conclusion, the significant buried structures revealed by geophysical methods under the cathedral were confirmed by recent archaeological digging as the basement of the impressive Roman Temple that headed the Provincial Forum of Tarraco, seat of the Concilium of Hispania Citerior Province.

Introduction

Tarragona's cathedral is located on the highest topographical site of the city. Romans occupied this space in the IIIrd century B.C. and converted it into a military camp, from where it waged the wars in the Iberian Peninsula against the Carthaginians commanded by Hannibal. Subsequently, Tarraco was the arrival point for the Roman soldiers who started the conquest of Hispania. The town of Tarraco is the first and oldest Roman settlement on the Iberian Peninsula and became the capital of the Province of Hispania Citerior during the reign of Augustus. As such, it was suitably endowed with imposing public buildings, as a demonstration of Roman power. It was visited by several Roman emperors, among them Augustus and Hadrian, and was the site of many councils bringing together officials. The unique Roman plan of the town is exceptional, as it adapted to the contours of the land by means of a series of artificial terraces, which are to be seen around the provincial forum as well as in the residential quarter.
After gaining the rank of provincial capital, Tarraco started a series of urban transformations, presided over on the hill by a great sacred enclosure that surrounded the temple devoted to the emperor Augustus. It must be remembered that Roman worship was practised outside and not inside their temples. After the Christian religion became official in the Roman Empire, at the end of the IVth century A.D., the emperors ordered a gradual legislative process that favoured the replacement of pagan cults by Christian worship. At this time, the site underwent a strong process of changes in urban planning and ideological reassessments. During the Vth and VIth centuries, the urban elements of this zone changed radically, with residential spaces including openair waste dumpsand spaces for both civil and religious official ceremonies. This was also the context for the later building of the Medieval Cathedral, linked with the Bishop's Palace and burial ground spaces.

Methods

The geophysical methods used in this study area are based on the detection of variations in the electric and electromagnetic properties of the subsoil and the use of these data to identify artefacts and to distinguish between these and natural variations in the soil. Geophysical investigations play an important role in defining shallow subsurface structures. In particular, they are nondestructive and a costeffective way to locate buried structures in archaeological studies. Taking into account earlier experiences in other similar surveys, two complementary geophysical methods were planned: Electrical resistivity tomography and Ground probing radar (Casas et al., 2008).

The ERT survey used two different multichannel resistivity meters: an Iris Syscal Plus with 48 channels for recording 2D sections and a MRS256 System from GF Instruments with 350 channels for 3D models. In both cases, the procedure for data acquisition was to apply a DC electrical current by means of two electrodes and to measure the potential generated over two other electrodes placed by profiles (2DERT) or regular grids (3DERT) spaced one meter apart over the pavement (Cosentino et al., 2009).

For the bidimensional profiles, stainless steel flat base electrodes, similar to those used by Athanasiou et al. (2004), were employed. To decrease contact resistance, a conductive gel was placed between the metallic electrodes and the soil pavement. With this strategy, the contact resistance was set at below 10 kohms.

Twentytwo profiles were recorded both in transversal and longitudinal orientation, using a mixed WennerSchlumberger array, giving up to six thousand apparent resistivity values. Also, for 3D acquisition, the main technical problem affecting the measurements was caused by the contact resistance at the potential electrodes. In fact, we needed smallsized electrodes with limited but similar contact resistance. A good choice was the use of disposable Foam Ag/AgCl ECG electrodes.

The large amount of data produced by multielectrode systems requires automated data handling and processing. To obtain a more accurate picture of the subsurface, it is necessary to invert the apparent resistivity data. The inversion method was based on the smoothnessconstrained leastsquares method. In this method, the subsurface is divided into cells of fixed dimensions for which the resistivities are adjusted iteratively until an acceptable agreement between the input data and the model responses is achieved, based on a nonlinear optimization technique by leastsquares fitting (Loke and Barker, 1996). During the inversion process, the root mean square value of the difference between experimental data and the updated model response is used as a criterion to assess the convergence.

The GPR survey used a Subsurface Interface Radar System (SIR 3000), manufactured by Geophysical Survey Systems, GSSI, with two antennae with centre frequencies of 270 and 100 MHz. Most of the survey used the 270 MHz antenna, because the resolution obtained with the 100 MHz antenna was too low to be effective. Appropriate data processing stacking, filtering, migration and advanced visualization techniques were applied to help understand and interpret GPR data. In addition, to obtain a significant "picture" of the underground electromagnetic discontinuities, both 3D data collection along closelyspaced parallel survey lines, with sufficient spatial sampling to reduce aliasing problems, and timeconsuming 3D data processing were required.

The surface of the temple was surveyed by a grid of profiles spaced 0.4 m apart and a horizontal resolution of 0.02 m (50 scans per meter). Due to the need to have the greatest resolution on the central nave, a perpendicular grid was traced in order to obtain recordings in both directions. Close parallel profiles allowed the assembly of GPR time slices, which made it easy to correlate anomalies recorded at the same time. This is one of the most useful data presentations for understanding the nature of subsurface structures over large areas at different depths (Goodman et al., 1995). Depths were calculated from an approximate velocity analysis based on the geometry of hyperboles.

Geophysical results

The preliminary results of this survey gave us an idea of the archaeological potential of the anomalies after processing the geophysical data. One of the main results is that the erection of the Medieval Cathedral did not involve the complete removal of other elements in order to reach the bedrock.

The anomaly with high resistivity values up to 2000 W·m that appears in the central part of most of the 2D ERT profiles was interpreted as showing remains of the basement of Augustus' temple (Figure 1a). GPR analysis showed the existence of archaeological stratigraphy. Data analysis suggested depth alterations and differences between the central and the lateral naves, as well as between the central nave and the main entrance to the medieval temple (Figure 1b). A general characteristic of the surveyed area is the good penetration of electromagnetic energy, 100 ns, corresponding to a depth of about 4.0 m when a mean velocity value of 0.08 m/ns is used. This is essentially due to the physical characteristics of the materials used for the construction of the temple (limestone), which have high resistivity values and therefore dissipate the EM energy only slightly.

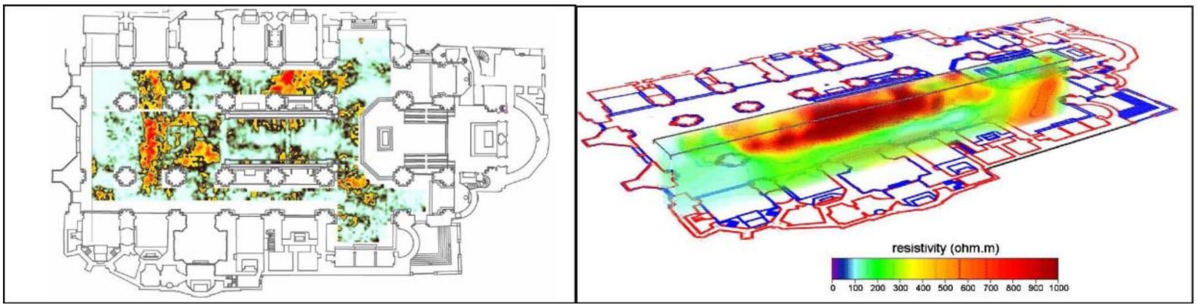

Figure 1. Left: High resistivity anomaly detected from the inversion of the 3D ERT survey. Right: Time-slice from 1.0 to 1.2 meters depths derived from GPR signals recorded with the 270 MHz antenna.

Archaeological results

From June to November 2010 a selective archaeological excavation was carried out until the remains illustrated by the geophysical surveys and interpreted as the foundations of the old Roman Temple of Augustus were reached. The aim of the dig was to evaluate the geophysical results. Two boreholes (SR1 and SR2) were drilled by a Tecoinsa TP50D drill machine. The first borehole (SR1) was placed above the low resistivity zone, interpreted as clay sediments, closer to the main entrance of the Cathedral and the second one (SR2) was placed over the high resistivity layer interpreted as the basement of the Temple (Figure 2).

The precise location of Augustus' temple, a cause of debate since the 16th century, was confirmed. It occupies most of the central nave of the cathedral, measuring 22 metres wide and 35 metres long. (Macías et al, 2007). Other similar temples built during the same period suggest that the front of the temple had 8 columns, as is represented on contemporary coins (Figure 4). After being studied and documented, the remains were protected and covered again by the medieval pavement of the Cathedral.

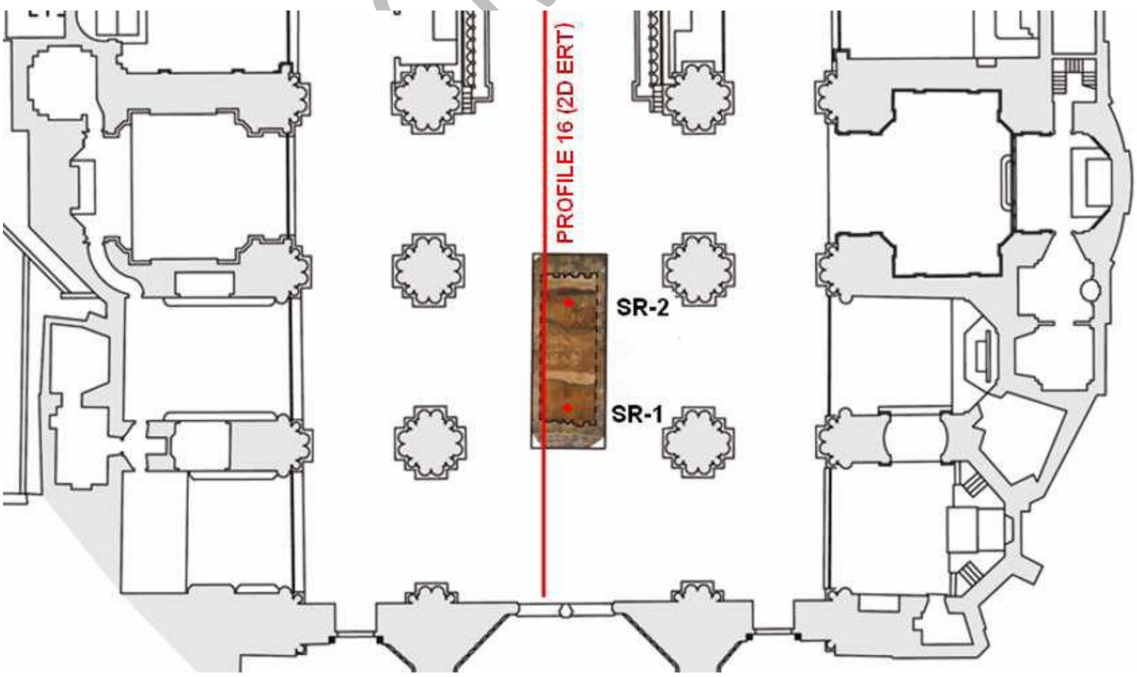

Figure 2. Location of the archaeological digging (rectangular area) and the two boreholes (SR1 and SR2) related two one 2D ERT profile used for the comparative interpretation.

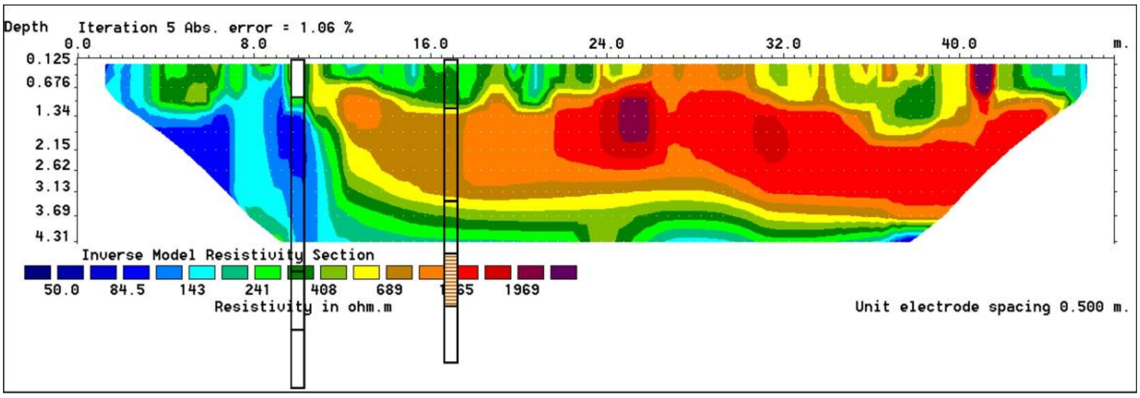

Figure 3. Inverted 2D resistivity of the profile 16 with the logs of the two boreholes overimposed

Conclusions

The effectiveness of the different geophysical methods in mapping the archaeological features under Tarragona Cathedral was confirmed. The structure of the temple basement was revealed by both 2D and 3D electrical imaging techniques. The results indicate that the use of flat-base electrodes instead of standard pointed electrodes is a very good alternative at sites that cannot be pinpointed. As they have the advantage of being completely non-destructive, they expand the use of geoelectrical methods into environments that otherwise we would never consider.
Definition of the location and size of the foundations of the Roman Temple of Augustus is based on the comparative study between selective archaeological excavation and geophysical anomalies. It should be pointed out that the geometry of the anomalies derived from the geophysical surveys conducted in September 2007 was corroborated by the archaeological evidence.

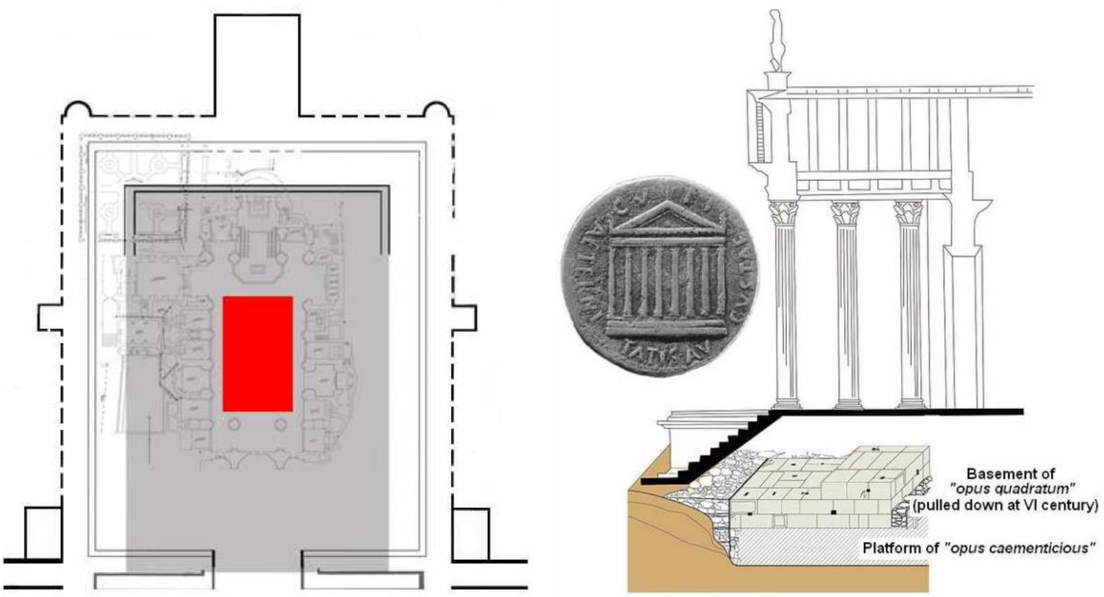

Figure 4. At left: Location of the temple depicted as a red rectangle in the central part of the Roman Forum and almost coincident with the central nave of the Cathedral. At right: Idealized image of the temple based on the archaeological results and the image of the front side depicted in the coin.

Acknowledgements

The authors are indebted to Jaume Pujol (Archbishop of Tarragona's Cathedral), Josep Martí (Diocesan Delegate for Heritage), Francesc Gallart (Dean of the Bishop's Chapter) and Isabel Rodà (Director of the Catalan Institute for Classical Archaeology).

References

- Athanasiou, E., Tsourlos, P., Tsokas, G., Papazachos, C., Vargemezis, G. 2007. Nondestructive DC Resistivity Surveying Using Flat Base Electrodes. Near Surface Geophysics, 5(4), 263272.
- Casas, A. Consentino, P.L., Díaz, Y., Fiandaca, G., García, E., Himi, M., Lafuente, R. Martorana, R., Macias, J.M., Menchón, J., Muñoz, A., Sala, R., Teixell, I. 2008. Integrated archeological and geophysical Survey for searching the roman's Augustus Temple in Tarragona (Spain). The material and the signs of history. I Quaderni di Palazzo Montalbo 15, 273283.
- Cosentino, P.L., Casas, A., Capizzi, P., Díaz, Y., Fiandaca, G., García, E., Himi, M., Martorana, R., Sala, R. 2009. Integrated Geophysical Surveys in the Tarragona Cathedral. Proceedings of the 15th European Meeting of Environmental and Engineering Geophysics. Dublin, Ireland
- Goodman, D., Nishimura, Y., Rogers, J.D, 1995. GPR time slices in archaeological prospection: Archaeological Prospection, 2, 8589.
- Loke M.H., Barker R.D. 1996. Rapid leastsquares inversion of apparent resistivity pseudosections by a quasiNewton method. Geophysical Prospecting, 44, 131152.
- Macías, J.Mª, Menchón, J.J., Muñoz, A., Teixell, I. 2007. Excavaciones en la catedral de Tarragona y su entorno: avances y retrocesos en la investigación sobre el Culto Imperial. In: Proceedings of the meeting Culto Imperial: política y poder (In: T. Noguera and J. González, Eds.), 765-787.