Archeologia e Calcolatori
Supplemento 11, 2019, 77-84

GROUND PENETRATING RADAR SURVEY

1. Introduction

It is now widely accepted that archaeological sites are increasingly threatened and non-renewable cultural resources (Campana, Piro 2009). The prudent management of our cultural heritage calls for the non-invasive assessment of sites not under threat, the evaluation of sites in areas open to change, and the identification and recovery of information where sites are to be destroyed. Archaeological sites, for example, represent a particular environment with a high monumental, artistic, and historical value whose protection needs to reconcile two fundamental, if different, requirements: on the one hand is the preservation of ancient history and, on the other hand, the requirements of urban growth and conversion.

In urban planning, such sites should be viewed as areas worthy of revitalization, improvement and regeneration, with planning and development undertaken for both socio-economic and touristic purposes. Doclea is an example of a complex environment in which the overlapping of architecture from different chronological phases down the centuries creates critical problems of conservation and management of cultural heritage.

2. The role of high-resolution geophysics

In a context like this, high-resolution geophysics can play a key role. Generally, such investigations are carried out using different 2D and 3D tomographic approaches, as well as different energy sources: sonic and ultrasonic waves, electromagnetic (inductive and impulsive) sources and electric potential fields. The acquired tridimensional matrix of data, properly treated using physical and mathematical algorithms of data processing, provides a detailed 3D screening of the hidden and invisible features of the objects and environments in the area investigated. The set of data produced allows archaeologists, scientists and experts in enhancement of cultural heritage to possess a comprehensive model that can be used in excavation planning, restoration projects and reconstructive processes, or can be visualized in interactive modes within a museum. The reconstructed models enhance the perception of the historical value of a place.

The application of geophysical methods for archaeological prospection and cultural heritage dates back to the early 1950s. The main techniques used for diagnostics of cultural heritage are: the magnetic-field method, gravitational surveying, electromagnetic methods, Ground Penetrating Radar, Electrical Resistivity Tomography (ERT), and the Self-Potential (SP) method

(Witten 2006; Campana, Piro 2009; Scollar *et al.* 2009; Schmidt *et al.* 2015; Cozzolino *et al.* 2018).

The evaluation of the appropriate survey methodology to be used is a very important factor that, if misjudged, can seriously undermine the success of research for archaeological purposes. This choice depends on many factors: geological, economic, logistic and purely geophysical ones. A decision is principally effected by considering the purpose of the exploration and by the dissimilarities possessed by the geophysical properties of the expected features in the subsoil that through the stronger or weaker anomalies recovered will define the supposed structure. The matters on which geophysics are employed may concern tombs, foundations of buildings, furnaces, canals, trenches, etc. or be connected with the resolution of problems related to the restoration of buildings of historical interest, such as in cases where it is necessary to assess the extent of fractures or water infiltration in the walls. Depending on the type of problem, the environment in which one is working and the type of instrumentation to be used, the methodology that will give the best results is selected.

3. The GPR at Doclea

Taking into account the probable type, dimensions and depth of the submerged structures and the geological characterization of the soil, Ground Penetrating Radar was chosen in the case of Doclea (Fig. 1).

GPR is one of the methods that have received a broader consensus and approval among archaeologists (Conyers, Goodman 1997) because of its capability to acquire data fast and to produce high resolution maps of structures located at depths ranging from a few tens of centimeters to a few meters. The advantages of GPR surveying are documented in many works dealing with applications in locating subsurface archaeological structures (Goodman *et al.* 1993; Malagodi *et al.* 1996; Basile *et al.* 2000; Pipan *et al.* 2001; Cozzolino *et al.* 2018, 105-110, 125-138) and also to image large scale archaeological features (Nishimura *et al.* 2000; Neubauer *et al.* 2002; Piro *et al.* 2001, 2003; Linford 2004; Cozzolino *et al.* 2018, 151-168). To investigate the subsoil, this method uses electromagnetic waves that are dispersed into the ground through a sending antenna placed on the surface; when they reach a discontinuity, they are partly transmitted (continuing their path through the material) and partly reflected back towards the surface where they are detected by a receiving antenna. The pulses received by the antenna in reception mode are passed to a central unit that converts them into digital format and stores them in an internal memory. The reflections mentioned are generally caused by changes in the electrical properties of the soil, changes in its water content or lithological variations. From the measurement of the travelling times of the pulses, if the propagation velocity in the subsoil is known,

Fig. 1 – IDS RIS-K2 Georadar during data acquisition.

the depth they reached may be estimated accurately too. The performance of the system is influenced by the electromagnetic properties of the medium they are used on: this determines the depth the survey can reach, which varies, therefore, from point to point.

Since 2016, an extensive survey has been conducted at the archaeological site of Doclea in the areas between the *forum*, the *basilica*, the *Capitolium*, the *thermae* and the walls of the city, around the eastern medieval churches, in the southern part of the temple of Dea Roma and of the private houses. GPR surveys have partly overlapped the areas between the *Capitolium* and the N walls investigated in 2007 through magnetometry, carried out as a joint research project between the British School at Rome (BSR) and the Archaeological Prospection Services of Southampton (APSS) (Pett 2010, 19). The results obtained in the remaining areas investigated in this research represent new and unpublished data.

An IDS RIS-K2 Georadar, equipped with a multi-frequency antenna TRMF (600-200 MHz), has been used for data acquisition. All radar reflections were recorded digitally in the field as 16 bit data and 512 samples per radar scan. The spacing between parallel profiles at the site was 0.5 m and they were collected alternatively in opposite directions with angles of 90 degrees to the survey grids. Radar reflections on each line were recorded at 25 scan s^{-1} (1 scan approximately corresponds to 0.025 m).

Standard bi-dimensional radargrams relative to single transects were processed through the GPR-SLICE 7.0 software. Band pass filters, background removal and Gain Control were applied in order to remove high and low

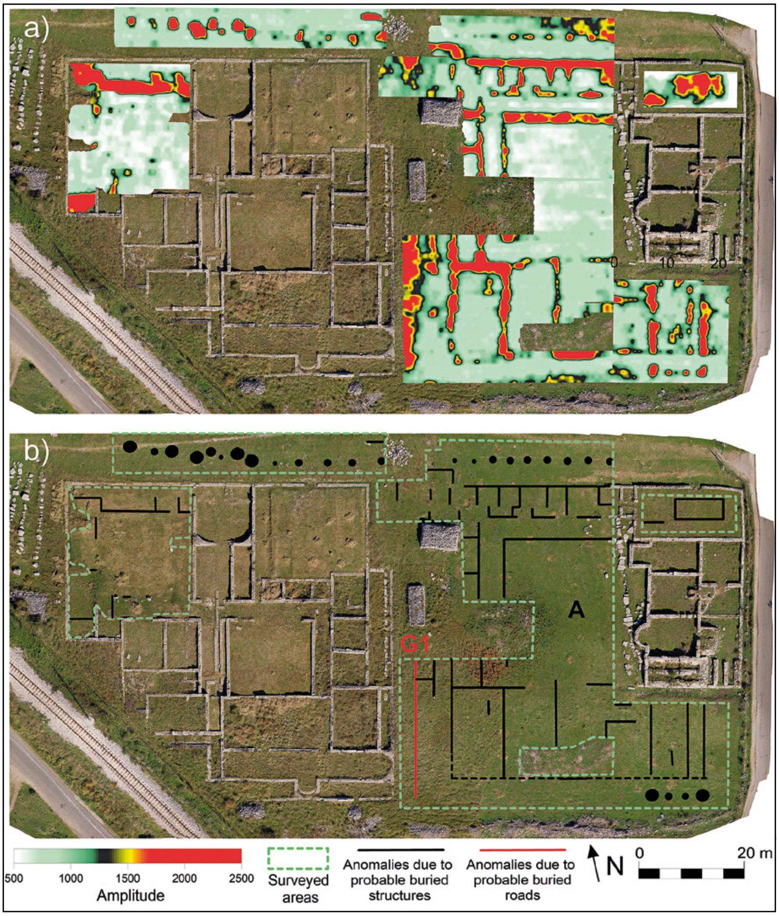

Fig. 2 – GPR results between the *thermae*: time slice relative to the time window 14-18 ns (about 0.7-1.4 m in depth), overlapped on the photogrammetric image (a) and identification of anomalies (b).

frequency anomalies that occurred during the data acquisition, normalize the amplification and remove reflections generated by noise due to the different signal attenuation (Conyers, Goodman 1997; Goodman, Piro 2013).

Thus, using a sequence of parallel lines, a three-dimensional matrix of averaged square wave amplitudes of the return reflection was generated and time-slices were realized for various time windows. In the examined context, considering a conductive soil with a velocity v with which the wave spread into the materials equal to 0,1 m/ns, the depth h of the reflectors can be approximately derived using the equation $h = vt/2$ (where t is the time in

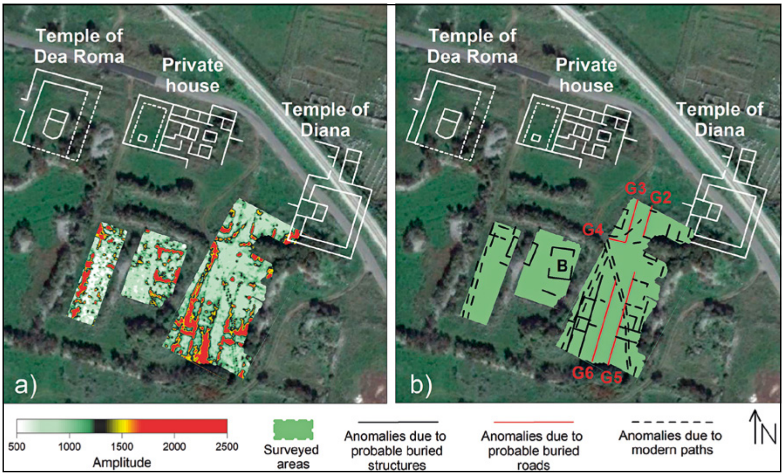

Fig. 3 – GPR results in the southern part of the private houses: time slice relative to the time window 14-18 ns (about 0,7-1,4 m in depth), overlapped on the photogrammetric image (a) and identification of anomalies (b).

which the electromagnetic wave fulfils the path transmitter antenna-discontinuity-receiver antenna). Data was then gridded using a kriging routine and a radius of interpolation equal to 0.75 m.

4. GPR survey results

Plate 4a presents the results of GPR investigations carried out around the *thermae,* the *Capitolium*, in the space in the southern part of the private house and in the southern sector of the northern walls, relative to the time window 14-18 ns (about 0.7-1.4 m in depth), overlapped on the satellite image of Google Earth™. The anomalies seen in these representations depict the spatial distribution of the amplitudes of the reflections at specific depths within the grid. Within the slice, low amplitude variations express small reflections from the subsurface and, therefore, indicate the presence of homogeneous material. High amplitudes denote significant discontinuities in the ground and evidence the presence of probable buried objects.

In Plate 4b, an interpretation of anomalies is attempted and the plan of probable inner walls is given. In particular, both different rooms around the *thermae* and an open space (a probable courtyard, signed with letter A) between the two thermal baths are well imaged, as well as some hypothetical bases of columns (black circles equally spaced) at the southern border of the *decumanus* (Fig. 2). The G1 anomaly (Plate 3) could be a border of the *cardo* that crosses the *thermae*. In the southern part of the private houses, even if

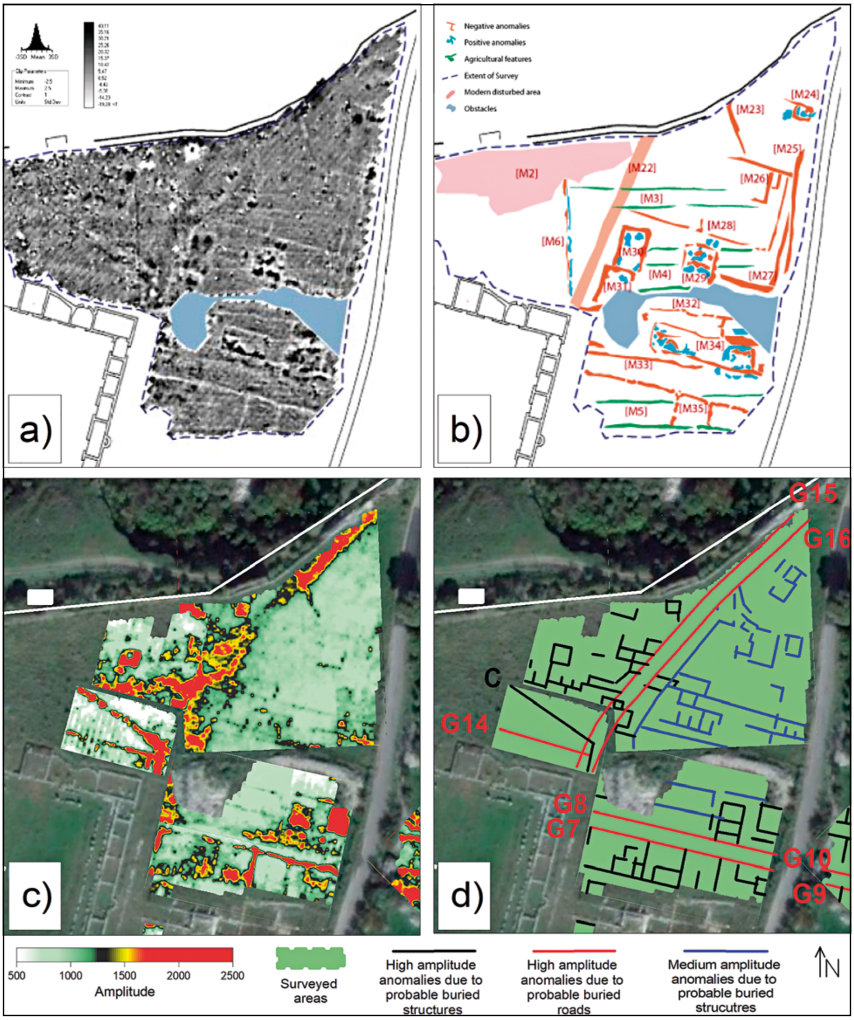

Fig. 4 – Comparison between GPR results and magnetometry results (Pett 2010) among the *Capitolium* and the northern walls: a) Magnetometry results greyscale (Pett 2010, 25), b) Magnetometry results interpretation (Pett 2010, 29), c) GPR results, d) GPR interpretation.

there are some disturbance due to the presence of modern paths (signed with dotted black lines), interesting anomalies are shown. In detail, the investigations evidence the presence of traces of structures (Fig. 2, Plate 3 and Plate 4b) that overlap the probable roads (indicated with red lines in Plate 4b). They are oriented according to the urban scheme, with the exception of the central rectangular anomaly, of dimension 18×12 m (indicated by the letter B in Fig. 3 and Plate 4b).

Different squared maxima of amplitude are associated with linear anomalies (in red lines, G2-G6 anomalies in Plate 3 and Plate 4b), whose projection into the northern sector of the city cuts the *decumanus* perpendicularly: it can thus be attributed to a *cardo* and gives important information on the division of the city into *insulae*. Other traces of the roads are visible in the NE part of the *Capitolium* (G7-G16 anomalies in Plate 3 and Plate 4b). Finally, some irregularities in the urban scheme stand out: in the northern sector, the road curves towards the N gate (G15 and G16 anomalies in Plate 3 and Plate 4b), departing from the regular pattern visible in the S (G9-G13 anomalies in Plate 3 and Plate 4b); to the W of the churches, the pattern of streets identified gives a block width of 75 m.

The results of the GPR investigations are perfectly in line with the results of the previous magnetometric surveys between the *Capitolium* and the N walls even if, considering medium amplitude anomalies, it is now possible to recognize some additional elements as shown in Fig. 4c, d and Plate 4b. A noticeable difference was found in the definition of the continuation of the road that flanks the *forum* to the E: while the magnetometry detects an indistinct positive feature that runs from the SE corner of the *forum* in a NNE direction[1], GPR survey, to the analysed depth, highlights an anomaly initially oriented in the direction NNE but then curving to flank the N walls (G15 and G16 anomalies in Plate 3, Plate 4b and Fig. 4). In addition, the C anomaly, a probable piece of buried water pipeline, and the G14 anomaly (Fig. 4c-d) are slightly visible in the magnetometry results (Fig. 4a, Pett 2010, 25) as negative anomalies even if they are not interpreted in Fig. 4b (Pett 2010, p. 29).

Work is still proceeding: the main objective is to produce a full map of the hidden structures inside the walls of the city. Such would be invaluable in guiding archaeological excavation and in assisting in the valorisation of the site.

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[1] «There is a broad and indistinct positive feature [M22] that runs from the SE corner of the forum in a N-NE direction. It is possible that this too represents an older boundary marker. On the 1907 Sciotti Map there is a line marked in this location, which could possibly be a field boundary. Alternatively, the alignment of this anomaly supports the theory that this could represent a continuation of the street that runs NNE alongside the forum itself» (Pett 2010, 24).

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ABSTRACT

Since 2016, an extensive survey has been conducted at the archaeological site of Doclea in the areas between the *forum*, the *basilica*, the *Capitolium*, the *thermae* and the walls of the city, as well as around the eastern medieval churches, and in the S part of the temple of Dea Roma and of the private house. GPR results have produced a detailed and extensive plan of hidden structures (walls, roads, ditches and gullies) inside the walls of the city. The knowledge of these features is of great worth in promoting archaeological excavations and projects of valorisation for the site.