Integrated Geophysical Study of Archaeological Sites in the Aquileia Area

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Abstract. Integrated remote sensing and geophysical methods can provide detailed information about buried cultural heritage. We implemented an integrated survey protocol (IREGA, Integrated REmote-sensing and Geophysical prospecting for Archaeology) and tested the performance of the method in the area of the ancient Roman town of Aquileia, NE Italy, to define and characterize micro-areas of archaeological interest starting from macro-area observations. We used electromagnetic (GPR; ground-penetrating radar), magnetic and remote sensing (MIVIS; Multispectral Infrared and Visible Imaging Spectrometer) to image and characterize buried targets of potential archaeological interest in the depth range between 100 and 350 cm. We identified various geometrically coherent anomalies, possibly related to subsurface structures, through MIVIS data processing and found them in good agreement with the elements reported in the Aquileia archaeological map obtained from documentary evidence and excavations performed in the last century. Ultra High Resolution (UHR) Multi-Fold (MF) Ground-penetrating Radar (GPR) and magnetic surveys confirmed the MIVIS results and allowed imaging and mapping of buried structure related to different Roman remains (SE sector of the Circus, harbor and residential buildings foundations, roads).

Keywords: Geophysics, Archaeology, Ground-penetrating Radar, Magnetometry, Remote Sensing

1 Introduction

The research of buried archaeological structures requires a detailed knowledge of the shallow subsurface and a methodological approach designed to define areas of maximum interest where surface data collection and successive excavation should be planned. The definition of macro-areas can take advantage of remotely-sensed data or Digital Elevation Model (DEM) characterized by metric spatial horizontal resolution and millimetric spatial vertical resolution respectively (e.g. Barnes, 2003; Flower J.F.M., 2002), while detailed studies require the use of Ultra-High-Resolution (UHR) non-invasive geophysical methods to define the geometry and depth of the identified targets (e.g. Pipan et al.,1999a; Lück et al., 2003). The Aquileia Archaeological Park (NE-Italy) is an ideal site to test the integration of methods, due to the variety of targets and subsurface conditions and to the large amount of documentary evidences and archaeological excavations, that can be used in the calibration of results.

Aquileia is a Roman archeological site covered by alluvial sediments and characterized by a shallow water table (Arnaud-Fassetta et al.,2003). It was founded in the second century B.C. and rapidly became one of the most important fluvial harbors of the Roman Empire (Tavano, 1986). Since 1998 is in the UNESCO Register of World Heritage.

During the last ten years, we have been collecting a large amount of UHR geophysical datasets to identify archaeological structures buried in the area. Several studies (see Del Ben et al., 1995; Finetti et al., 1995a/b; Forte et al., 2006; Pipan et al., 1996a/b/c/d, 1997a/b, 1999a/b/c/d, 2003, 2004, 2005, 2007; Prizzon, 2003) give evidence of the extension and characteristics of the buried cultural heritage and provide detailed information about subsurface conditions, which complement the results of archaeological excavations and the available documents. In this study, we focus on the integration of advanced methods (MIVIS, multi-fold GPR, magnetic gradiometry, electrical resistivity tomography) to provide new information about the buried cultural heritage in the Aquileia area, with specific reference to the areas of the Circus, the Forum, the river harbor and the remains of a building in the outskirts of the imperial town (Fig.1).

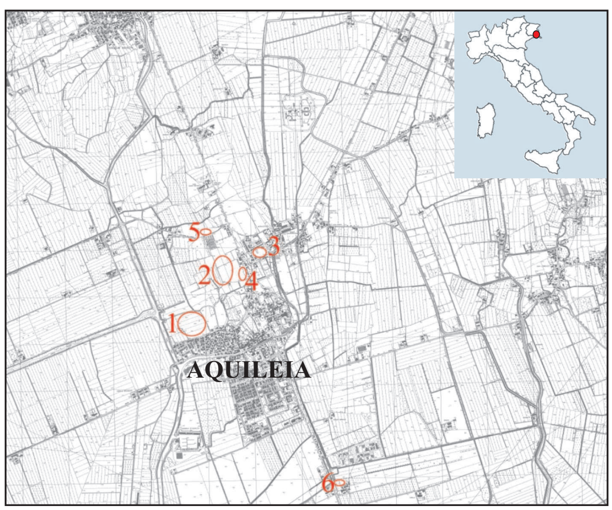

Fig. 1. Location map of the archaeological sites surveyed in the Aquileia area [from the Technical Regional Map (CTNR, 2003)].

2 Methods

The proposed methodological integration (IREGA) for the non-invasive study of archaeological sites is based on the analysis of the following data: MIVIS, magnetic and GPR. At selected locations, Electrical Resistivity Tomography is also included, for an integrated analysis of the electric properties of the buried materials. The MIVIS system has 4 optical ports with 102 spectral bands - ranging from 0.431 to 12.7 μm and a spatial resolution about 3.0 m/pixel with a fly height of 1500 meters above sea level.Its effectiveness in archaeological prospecting depends on the characteristics of both the landscape and the buried structures. In fact, archaeological buried objects can influence soil moisture and temperature, growth and health of the vegetation with anomalies marked out by different brightness (related to reflectance and temperature pixel value) and peculiar geometric shape.

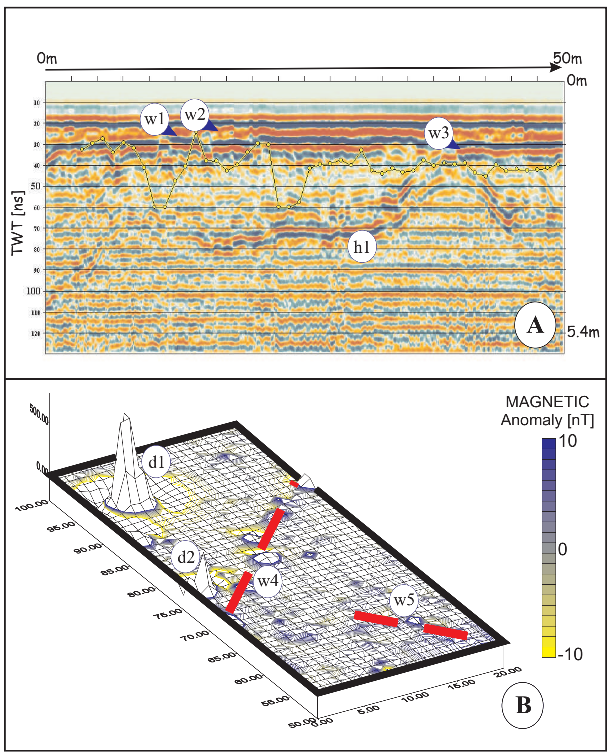

Fig. 2. Example of integrated geophysical surveys at site 6 (see Fig.1): A) GPR 200MHz stack section with magnetic data superimposed (in yellow); B) interpreted magnetic map. w1, w2 and w3: buried foundations remains; h1: contact between soil layers; dn : large dipolar magnetic anomalies due to shallow metallic materials; w4, w5: anomalies related to archaeological targets.

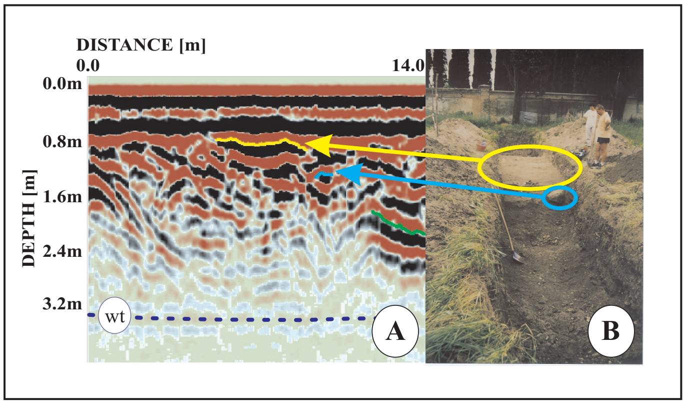

Fig. 3. GPR survey at site 5 (see Fig.1; northern limit of the actual cemetery): A) example of processed multi-fold 200MHz GPR profile; C) Excavation trench: yellow = road section revealed by GPR data; azure = stone block at the margin of the road; wt = water table.

The magnetic method measures variations of the Earth's magnetic field. It is an effective technique in archaeological prospecting to detect variations of magnetic susceptibility due to the presence of buried objects. Single-sensor and multi-sensor gradiometer measurements can be performed to detect magnetic anomalies due to buried archaeological remains (e.g., Becker and Fassbinder, 2001).

The term *Ground-Penetrating Radar* refers to a family of Ultra-Wide Band devices that use electromagnetic (EM) waves in the frequency range between approximately 10 MHz and 6 GHz to image and characterize the subsurface (see Daniels, 2004). Variations in EM properties of the subsurface materials affect wave propagation: they may produce diffraction, reflection and refraction phenomena and modify velocity and attenuation of EM waves. Penetration of such waves into the subsurface is influenced by frequency and by the electrical properties of the materials: in particular, it is reduced by increments of frequency and conductivity with a non-linear relation (from approximately 1 m in wet clay up to tens and hundreds of meters in dry sand and ice). 200-500 MHz antennas normally provide a suitable trade-off between resolution and penetration in the average soil conditions of archaeological sites in alluvial plains (e.g. Pipan et al.,1999).

MIVIS digital images were provided by Regione Friuli Venezia Giulia. We show here the results obtained from the analysis of thermal Infrared bands (93 to 102), whose temperature pixel values in ^{o}C were calculated with linear interpolation between referenced values of two black bodies. Ground pixel size corresponds to 3.0 meters.MIVIS data processing encompassed radiometric correction by means of principal component (PC) method, bad bands removal and geometric correction. Magnetic surveys were performed with a cesium magnetic gradiometer (SMARTMAG model SM-4), with a sensitivity of 0.01 nT and an operating range from 15000 to 100000 nT. Measurements were performed with two sensor located at 30 and 130 cm above ground level on NS

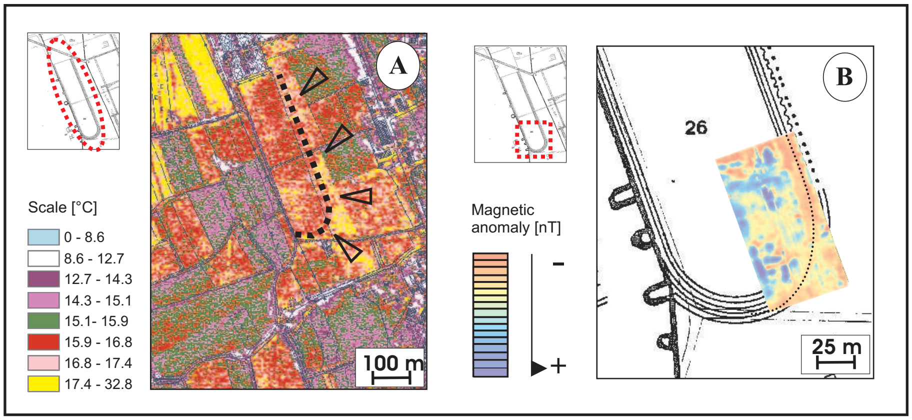

Fig. 4. Aquileia circus: comparison between (A) MIVIS digital image, band 98 (thermal infrared), density slice visualization and (B) magnetic anomaly map obtained from Scintrex caesium magnetometer (2x10 cm in-line/cross-line spatial sampling).

oriented grids.. A low-pass filtering 3x3 matrix was applied to remove incoherent noise and enhance magnetic anomalies.

Magnetic and GPR data were both acquired on grids with 2 cm - 25 cm inline - crossline sampling interval. A MalåGeoscience GPR system equipped with 250 MHz central-frequency antennas was used to acquire single- and multi-fold (average 1200% fold) data. Minimum and maximum offset were set according to preliminary tests and range between 40 and 240 cm. The basic GPR processing sequence included Wavelet Transform based de-wow, background removal, amplitude analysis and corrections, spectral analysis, time-varying band pass filter and predictive deconvolution with operator length = 30 ns and prediction distance = 4 ns. The instantaneous attributes (amplitude, phase and frequency) of the radar trace were calculated by Wavelet Transform techniques (Guangyou and Pipan, 2003), which proved less sensitive to noise and allowed a detailed reconstruction of the archaeological features. Electrical Resistivity Tomography (ERT) was performed at selected sites with a multi-electrode (16) system, Wenner-Schlumberger array, maximum 48 m AB-offset. The data were inverted by using the Loke algorithm (Loke and Barker, 1996).

3 Results

Examples of complementary (GPR and magnetic) and individual (GPR) results are given in Figs.2,3,7. Figs.4,5,6 show the outcome of the integration of different techniques: MIVIS, magnetic, GPR, ERT.

GPR and magnetic data frequently provide mutually consistent results, but in some cases they give complementary information. Fig.2 shows a comparison between GPR and magnetic data from site 6 (see Fig.1): the yellow line superimposed on GPR data in Fig.2A is the variation of the magnetic field measured along the GPR profile. W1,2,3 are the locations of buried wall/foundation remains that can be interpreted on the GPR data but do not show a clear signature on the magnetic record (W3). W4,5 in Fig.2B are small variations (in the range of $\pm$10nT from average magnetic field) that exhibit geometric coherence and are actually related to buried brickwork.

At the N limit of the cemetery of Aquileia, a large 3-D multifold GPR dataset provides a detailed subsurface reconstruction. Fig.3 shows an example of a highly elusive target, namely an unpaved road close to the walls of the imperial town, imaged by GPR. In this case, the contrast in petrophysical properties – porosity, fluid content – is given by the different compaction of sediments of the road compared to the surrounding materials.

An example of integration of remote sensing (MIVIS) and geophysical (magnetic) surveys is shown in Fig.4. Thermal infrared band 98 (Fig.4A: arrows and dotted line) shows a clear anomaly characterized by homogeneous temperature values lower than the surrounding ones. The anomaly shows a good correlation with the position of the roman circus tentatively reported on the Aquileia archaeological map (inset between Figs.4A and 4B). The filtered magnetic map (Fig.4B) shows an excellent correlation with the position of the roman circus as reported on the archaeological map, and with the thermal infrared data. Nonetheless, MIVIS and magnetic data do not convey information about the third dimension, i.e. the depth and vertical cross-sections of the anomalies are unknown. Such information is given by the GPR record in Figs.5A,C. Targets a, b, c in the B-scan (Fig.5A) can be interpreted as buried remains within, at the edge and outside the roman circus, respectively. The agreement with the magnetic data is apparent and further confirmed by the comparison between the GPR time-slice (Fig.5C) and the magnetic map (Fig.5B).

In front of the excavated sector of the Roman Forum, a large unexplored field has been used to test the integration of GPR and ERT (Fig.6). The GPR B-scan (Fig.6B) and the ERT section (Fig.6C) are in good agreement and give evidence of a bulky sector characterized by higher resistivity and low attenuation of the EM wave. Such characteristics are consistent with materials normally found in buried walls/foundations. A complete map of the surveyed area with the integrated interpretation of GPR and ERT data is shown in Fig.6C. The interpreted subsurface targets exhibit orientation coincident with the exposed remains excavated in the nearby Forum area. The highest resolution attainable by non-invasive methods is illustrated by the multi-fold 3-D GPR results shown in Fig.7. Slices of the processed data volume (Fig.7A) or of the attribute volumes that can be calculated from the processed data (e.g. Fig.7B) give clear evidence of horizontal and vertical distribution of the targets. The interpretation superimposed on the GPR data (Fig.7C) and the final results, combined with the archaeological map of the neighboring site (Fig.7D) illustrate the horizontal and vertical distribution of targets.

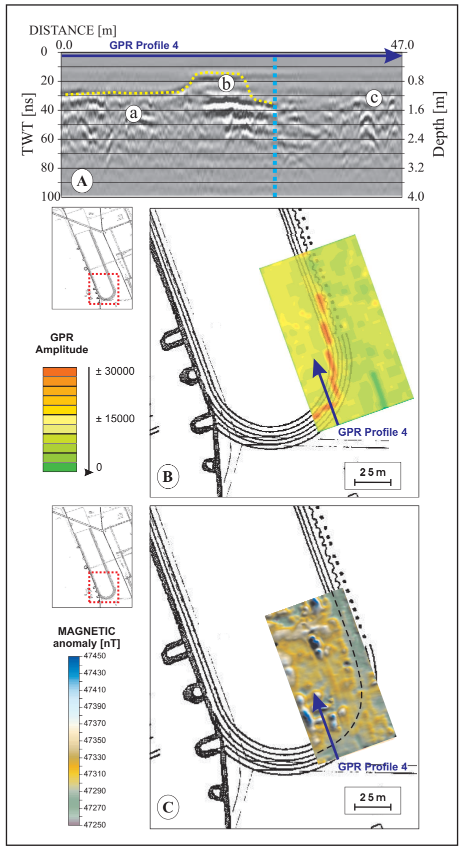

Fig. 5. The Aquileia circus, example of integrated GPR and magnetic data: A) GPR 200MHz profile; B) magnetic map; C) GPR amplitude depth slice (1m below the topographic surface). a) diffractions due to small objects within the circus; b) circus steps and border; c) small structure outside from the circus. The azure dotted line shows the external limit of the circus.

4 Conclusions

The tests performed in the Aquileia area indicate that the integration of different geophysical methods and the combination with remote sensing data analysis allow detailed and cost effective identification of targets of potential archaeological interest in large areas. MIVIS data allow the identification of areas of potential archaeological interest at macro-scale. Such information is obtained from the anomalies related to soil moisture and temperature. Ultra-High Resolution magnetic gradiometry and multi-fold GPR, with dense spatial sampling (i.e. average 5/25 cm in/cross-line respectively) are successively required to image and characterize targets before excavation. Areal geometry of the buried structures can be obtained by an integration of MIVIS, magnetic and GPR. Depth of the targets can only be obtained from GPR data, with accuracy depending on

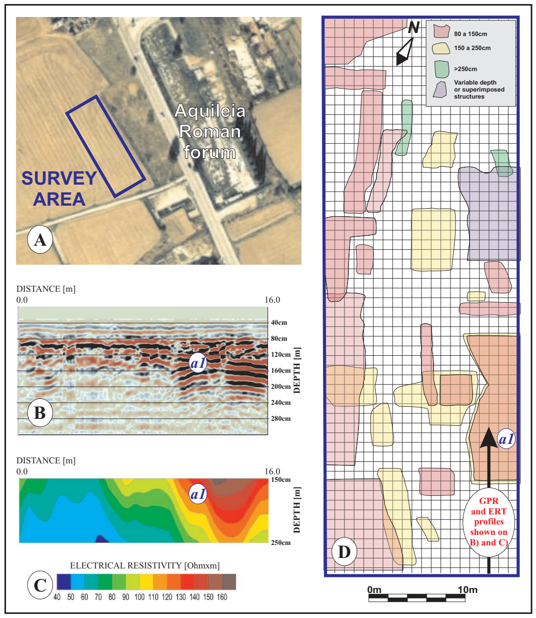

Fig. 6. The Aquileia roman forum: example of integrated GPR and resistivity study: A) Location map; B) GPR 200MHz multi-fold profile; C) Electrical resistivity: tomographic section (ERT); D) Map of the interpreted targets. Target a1 is clearly identified on both the GPR and ERT sections (see the text for details).

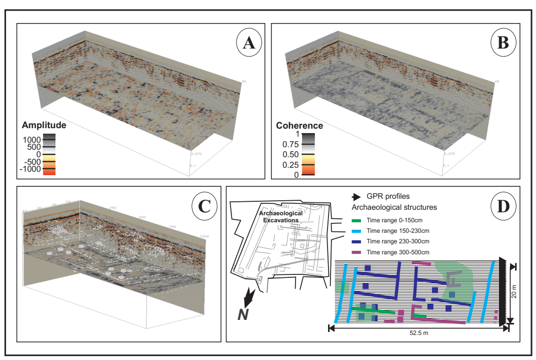

Fig. 7. The Aquileia river harbor: comparison between A) amplitude timeslice and B) coherence attribute calculated for the same position; C) Final interpretation of the 3D data volume. D) Comparison between geophysical results and map of archaeological remains from previous archaeological excavations next to the geophysical survey area.

the depth of the target. In the present study, targets in the depth range between 80 and 250 cm were identified with absolute uncertainty $\pm$ 5 cm. Electrical resistivity tomography can further help in the characterization of physical properties of the materials, since higher resistivities are normally correlated with stone, brickwork and foundation remains.

In this work, we studied four sites of potential interest. The largest structures revealed by the geophysical survey are the buried remains of the Circus, which exhibit a clear signature in all of the datasets (MIVIS, Magnetic, GPR; Figs. 4 and 5)). The analysis of 3-D GPR datasets allows the identification of further targets, which are below the resolution threshold of remote sensing methods. This is the case of the buried foundations and remains of walls in the forum and harbor areas (Figs. 6 and 7). Buried remains characterized by low contrast in physical properties (see e.g. the compact soil corresponding to the road, Fig.3, are also revealed by 3-D multi-fold GPR due to the high S/N ratio of the final images and the high sensitivity of the method to minor variations in water content. In some cases (e.g., site 6, Fig.2) magnetic and GPR data can provide complementary information and help in the identification of highly elusive targets.

Future developments should benefit from the integration of the proposed methods with high resolution topographic surveys of the areas of interest by means of airborne laserscan.

Acknowledgments

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