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GPR investigation to map the subsoil of the St. John Lateran Basilica (Rome, Italy)

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ABSTRACT The St. John Lateran Basilica is the Pope's Cathedral and the first public building constructed for Christian worship. The complex has been the focus of sundry excavations since the 1730s. These have revealed traces of the earliest phases of the building, along with parts of the *Castra Nova* of the Imperial Horseguard, a bath complex and palatial housing. Interpretation of these excavations is, however, difficult; and most of them are either undocumented or only partially recorded. The geophysical prospection is generally considered as the attempt to locate structures of archaeological interest buried in the natural subsoil, but in many cases, when applied in urban centres, this attempt could fail due to the effect and disturbances caused by recent man-made structures in the subsoil, covering any signal related to possible archaeological structures. In the present paper the ground penetrating radar (GPR) surveys carried out in the urban archaeological site of St. John Lateran Basilica, in Rome, characterised by different targets and environmental conditions, are presented and discussed. This site is characterized by artificial medium as road pavement, outside the basilica, and ancient buildings, below the current basilica. The paper illustrates the ground penetrating radar GPR surveys and the obtained results.

Key words: St. John Lateran Basilica, ground penetrating radar, urban geophysics, barracks of the imperial horse guards.

1. Introduction

1.1. The St. John Lateran Basilica complex

The archaeological area of the Lateran in Rome lies immediately within the Aurelian Walls near the gate of the *Via Tusculana*, under the Cathedral of St. John and the neighbouring buildings. It is an area of great historical importance. The *domus* of the first two centuries A.D. were superseded by the *Castra Nova Equitum Singularium* of Septimius Severus and later by the Constantinian Basilica and the Lateran bishopric.

An exceptional building in its own right, the Constantinian Basilica of S. Giovanni in Laterano holds the title of *caput et mater* of the churches of Catholic Christendom. The basilica is the Pope's own church, a pioneering structure and a site of remarkable archaeological importance.

Extensive excavations beneath the complex have revealed not only the remains of the first powerfully influential basilica and baptistery, but also structures from still earlier periods. Chief among these are the barracks of the imperial horse guards, substantial palatial buildings, a bath house, and a street with houses. These areas are remarkably well preserved and a substantial number of frescoes and mosaics remain *in situ*.

Extensive research by prof. Paolo Liverani (Florence University) has enriched our understanding of the complex, but a major collaborative project is required to interpret the remains unearthed by previous excavators. The earliest recorded excavations took place in 1730, the deepest lie 5.5 m below ground level.

This project is undertaking an intensive scientific survey of the entire structure to integrate information from standing buildings, excavated structures and sub-surface features through the collaboration of Newcastle University (UK), Florence University (Italy) and Institute for Technologies Applied to Cultural Heritage (ITABC-CNR, Italy).

1.2. Research design

The Lateran project aims to undertake a fully integrated 3D survey of the excavations under San Giovanni in Laterano.

A particular concern is to find an approach that will not only allow collaboration between researchers using a range of established and innovative methods, but also a method that allows an integrated approach to the three-levels of structural data that form the complex (Gaffney *et al.*, 2008). There are the standing features on the modern city surface, as seen in Fig. 1. These can only be fully understood in relation to subsurface features and vice versa.

There are also the extensive and inter-cut structures that form the opened area of excavations. Finally, there are the unexcavated deposits that lay either beyond the immediate confines of the site or beneath the area opened to date.

The aim of the ground penetrating radar (GPR) surveys is to identify Roman and high-medieval age remains which could enhance understanding of the ancient topography and the urban evolution of the study area. The main goals of this survey are the following (Fig. 1):

1. to determine the full plan of the Santa Croce Oratory, built by Pope Ilaro (5^{th} century) and destroyed by Sixtus the Fifth; part of this building has been identified by Olof Brandt within the excavated area adjacent to the Baptistery;
2. to determine the full extent of the palatial housing found below the western part of the Basilica;
3. to determine the limits of *Castra Nova Equiutum Singularium*, the barracks of the imperial horse guards established by the emperor Septimius Severus;
4. to locate the remains of the buildings of the Lateran Patriarchy. These are known from renaissance plans but up until now it has not proven possible to locate them all on the ground.

In the present paper, the results obtained to investigate the points 2, 3 and 4 are presented and discussed through the comparison with the hypothesis presented by the archaeologists.

Fig. 1 - Archaeological map of the St. John Lateran Basilica (Rome). The green colour indicate the areas investigated with GPR; the numbers are related to the objectives of the survey (courtesy of prof. P. Liverani).

2. Archaeological prospection in urban centres

There are many important research and technical issues related to the investigation in urban area to locate subsurface cavities and/or archaeological remains, to produce hazard mapping, that is of the highest priority, and archaeological risk map. This is especially so in civil engineering, where it is of key importance for managing safe urban and civil construction. In many cases, cavities, such as subsidence features, voids and collapses represent disruptions to the geometry of an originally near-horizontal layered system. Geophysical techniques can be used to identify the feature geometries by contrasts in the physical properties, but can be greatly impeded by cultural features that interfere with instrument measurements (utilities, structures, surficial debris).

Site preparation can facilitate the field work and can improve the accuracy of the geophysical surveys and interpretations. The most useful site preparations are performance of a topographic survey to create a site grid, placement of location markers and removal of surficial debris and obstructive vegetation. Conditions of the geophysical field project that are subjected to site-specific design include: selection of appropriate techniques, instruments, accessories and settings; performance of dual-technique surveys for redundant site coverage; performance of follow-up surveys and selection of instrument measurement density.

The critical phase of the geophysical survey in urban area is the interpretation of the collected data and the characterization of the degree of confidence in the interpretations.

The urban subsoil consists often of many layers documenting the history of a place, keeping records of alternating phases of construction and destruction. The shallow subsurface of modern cities contains reams of pipes, cellars, wells, cavities, tunnels, graves and foundation walls of former houses, churches and town fortifications. Underneath the tarmac of city roads and the paving stones of town squares layers of sand and gravel are criss-crossed with modern fibre optic and telephone cables and century old sewer pipes mixed with the debris of brick buildings.

The geophysical prospection of urban centres, which have been abandoned in the past and today are located under barren land, pose different methodological possibilities and challenges compared to surveys conducted in modern city centres.

While the first sites may successfully be prospected employing aerial photography, magnetometry, GPR, Earth resistance and inductive electromagnetic methods (Campana and Piro, 2009), many of these methods are difficult or impossible to use in the urban centre.

The most promising non-destructive geophysical prospection method for use in urban centres is GPR. GPR measurements are less affected by the presence of metallic structures compared to magnetometer prospection and they result in the largest amount of data of all commonly employed near-surface geophysical methods, providing detailed three-dimensional information about the subsurface (Utsi, 2006; Piscitelli *et al.*, 2007; Trinks *et al.*, 2009; Leucci *et al.*, 2011, 2012a, 2012b; Moscatelli *et al.*, 2013; Matera *et al.*, 2016). The GPR is an electromagnetic impulsive method much suited for shallow depth investigations, as it can supply subsurface profiles grouped in vertical radar sections. The transmitter-receiver antenna is pulled along the surface of a site, signals are sent with a highly directive radiation pattern into the ground and echoes are returned from targets in the ground within a few metres. The emitted radar signal is a pulse of electromagnetic radiation with nominal frequency value in the range 15-2500 MHz (1 MHz = 10^6 Hz). The velocity of an electromagnetic wave in air is 30 cm/ns (1 ns = 10^{-9} s). In soils the velocity is less, as typical values are in the range 5-15 cm/ns (Goodman and Piro, 2013).

While geophysical prospection is generally considered as the attempt to locate structures of archaeological interest, in many cases, when applied in urban centres, this attempt could fail due to the effect and disturbances caused by recent man-made structures in the subsoil, covering any signal related to structures of archaeological interest. Modern underground structures (as bars and slabs of reinforced concrete, metallic pipes, cables and associated trenches and building debris) occurring at shallow depth often display a stronger contrast in physical properties relative to the surrounding subsoil than less well expressed archaeological structures, which often are buried at greater depth.

Challenges for GPR prospection in city centres lie in the large number of obstacles present in the urban environments. Traffic islands, metallic gully covers, lamp posts, buildings, trees and parked vehicles cause irregular survey geometries, holes in the surveyed area and disturbing anomalies in the GPR measurements.

3. Data acquisition

For the measurements, outside and inside the St. John Lateran Basilica, a GPR SIR3000 (GSSI), equipped with a 400 MHz (GSSI) bistatic antenna with constant offset and a 70 MHz (Subecho

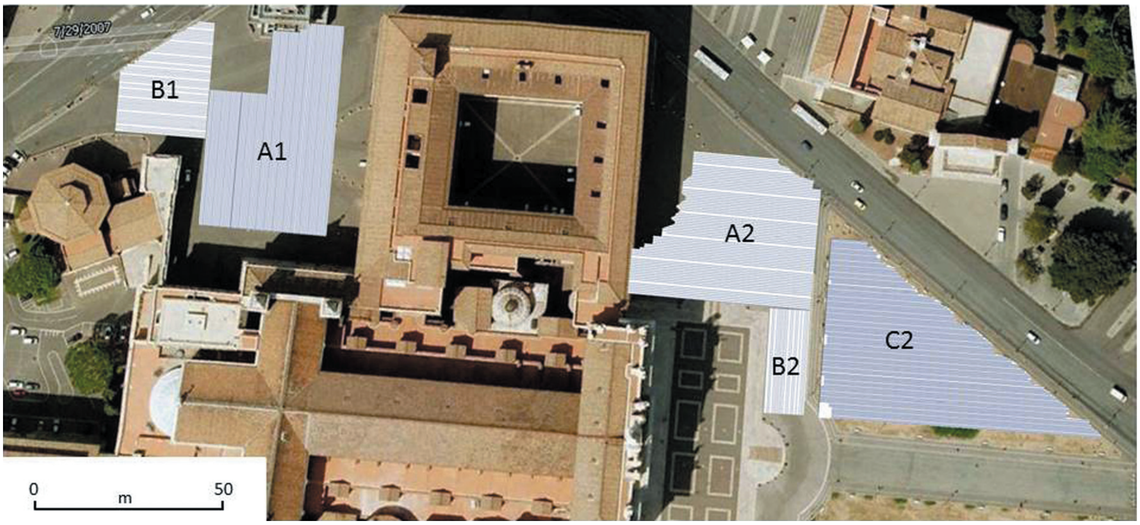

Fig. 2 - St. John Lateran square, Rome. Location of the area investigated with GPR systems.

Radar) monostatic antenna were employed. Some signal processing and representation techniques have been used for data elaboration and interpretation. GPR surveys were performed, employing the SIR3000 (GSSI) to survey the selected areas outside the Basilica in St. John Lateran square and inside the Basilica (Fig. 2).

The horizontal spacing between parallel profiles at the site was 0.50 m, employing the two antennas. Radar reflections along the transepts were recorded continuously, with different length, across the ground at 40 scan/s; horizontal stacking was set to 3 scans.

In the area outside the Basilica, a total of 777 adjacent profiles across the site were collected alternatively in forward and reverse directions employing the GSSI cart system equipped with odometer. All radar reflections within the 90 ns, for 400 MHz antenna, and 195 ns, for 70 MHz antenna, [two-way-travel (twt)] time window were recorded digitally in the field as 16 bit data and 512 samples per radar scan.

In the area inside the Basilica a total of 192 adjacent profiles across the four naves, the transept, and the entrance were collected alternatively in forward and reverse directions employing the GSSI cart system equipped with odometer. All radar reflections within the 120 ns for 400 MHz antenna (twt) time window were recorded digitally in the field as 16 bit data and 512 samples per radar scan.

Velocities of 0.08 m/ns and 0.10 m/ns, respectively outside and inside the Basilica, were estimated using hyperbolae fitting in GPR-SLICE v7.0 imaging software (Goodman, 2016).

4. Data processing and presentation

Reflection profiles were analyzed for preliminary identification of the buried features and for calibration of the instrument. Reflection data, collected in profiles with 0.50 m spacing, were processed using standard techniques (Neubauer *et al.*, 2002; Leckebusch, 2003, 2008; Conyers, 2004; Goodman *et al.*, 2004, 2009; Linford, 2004; Goodman and Piro, 2008, 2013; Piro and Goodman, 2008; Leucci *et al.*, 2011; Piro and Campana, 2012).

The basic radargram signal processing steps included: i) post processing pulse regaining; ii) DC drift removal; iii) trace resampling along the profile (an averaged trace every 4 cm); iv) band pass filtering; v) migration; and vi) background filter.

Reflection amplitude maps were constructed within various time (and corrected to depth) windows to show the size, shape, location and depth of subsurface archaeological structures (Neubauer *et al.*, 2002; Conyers, 2004; Gaffney *et al.*, 2004; Linford, 2004; Goodman and Piro, 2008, 2013; Leckebusch, 2008; Piro and Goodman, 2008; Goodman *et al.*, 2009). These images were created using the spatial averaged squared wave amplitudes of radar reflections in the horizontal as well as in the vertical direction. The squared amplitudes were averaged horizontally every 0.25 m along the reflection profiles 3 ns (for 400 MHz antenna) and 6 ns (for 70 MHz antenna) time windows (with a 10% overlapping of each slice). The resampled amplitudes were gridded using the inverse distance algorithm with a search radius of 0.75 m.

As examples, the unmigrated reflection profiles, collected in the sector A1 of the investigated area (Fig. 2), showing reflections from bodies in the ground at about 10 - 40 ns (twt), for 400 MHz and 20 - 60 ns (twt) for 70 MHz antenna, are presented in Figs. 3 and 4.

All the GPR data were processed in GPR-SLICE v7.0 Ground Penetrating Radar Imaging Software (Goodman, 2016).

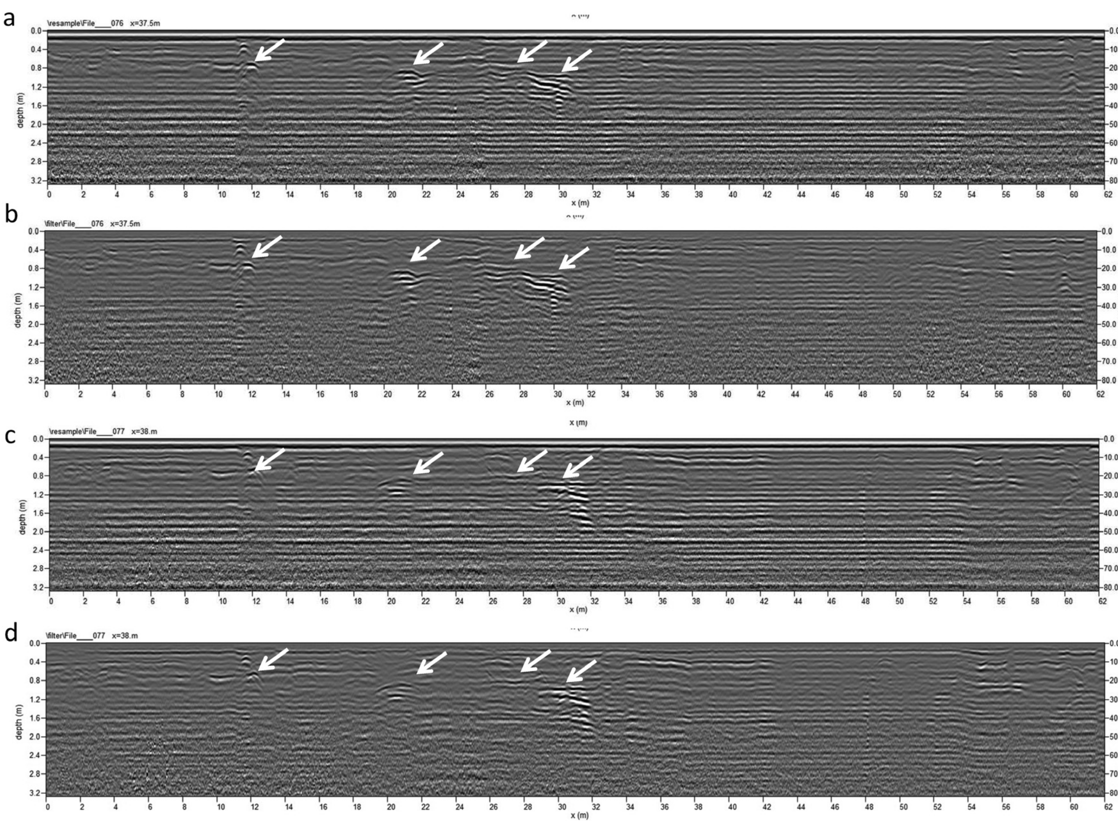

Fig. 3 - Examples of GPR profiles collected with 400 MHz antenna: a) and c) field profiles, b) and d) unmigrated filtered profiles.

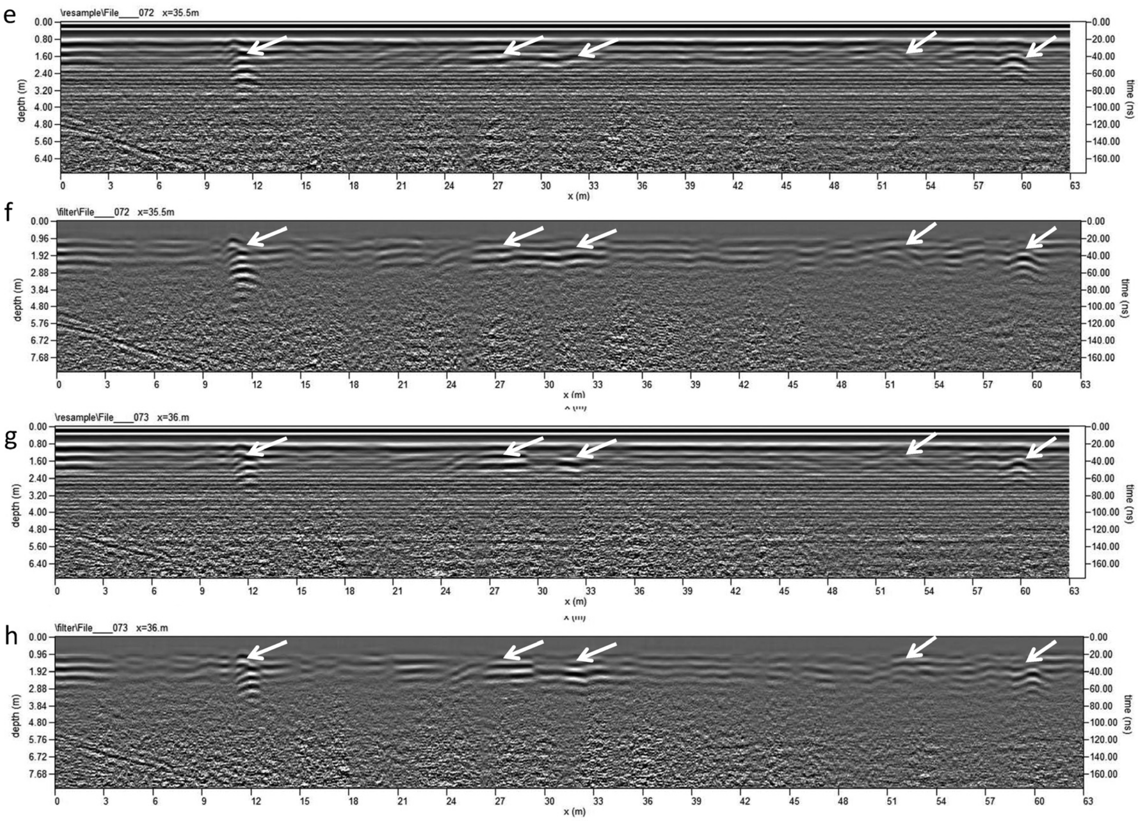

Fig. 4 - Examples of GPR profiles collected with 70 MHz antenna: e) and g) field profiles, f) and h) unmigrated filtered profiles.

5. Results and interpretation of the GPR data

5.1. St. John Lateran square - area A1 and B1 (antenna 400 MHz)

The GPR amplitude maps, related to the profiles collected with 400 MHz antenna have been analysed and our attention has been focused to the following time-windows: 19-22, 25-28, 30-34, 41-45, 47-50 and 58-61 ns (twt), corresponding to the averaged estimated depths of 0.88, 1.10, 1.30, 1.70, 2.00 and 2.40 m respectively, without considering the first portion of the subsoil which is characterised by the presence of many surface utilities.

Few GPR time-slices, characterised by interesting anomalies, are presented and described in the following figures, firstly for the St. John Lateran square and secondly for the area in front of the Basilica.

Fig. 5 shows the anomalies located at the estimated depth of 0.88 m [19-22 ns, (twt)], individuated in the area A1 and B1. At this depth, the area is characterized by many strong reflections due to the presence of utilities (6-7) and of portion of possible structures (1-2-3-4-5).

The size of the anomalies, indicated below, are approximate: (1) strong anomaly with linear orientation and dimension x: 13.0 m, y: 3.5 m; (2) anomaly with semi-circular orientation with diameter: 9.0 m and size 2.5 m; (3) anomaly with average dimension of x: 2.0 m, y: 7.0 m; (4) two parallel anomalies with average dimension x: 2.0 m, y: 7.0 m; (5) anomalies with different size and dimension 13.0×17.0 m; (6) and (7) anomalies due to utilities with different size.

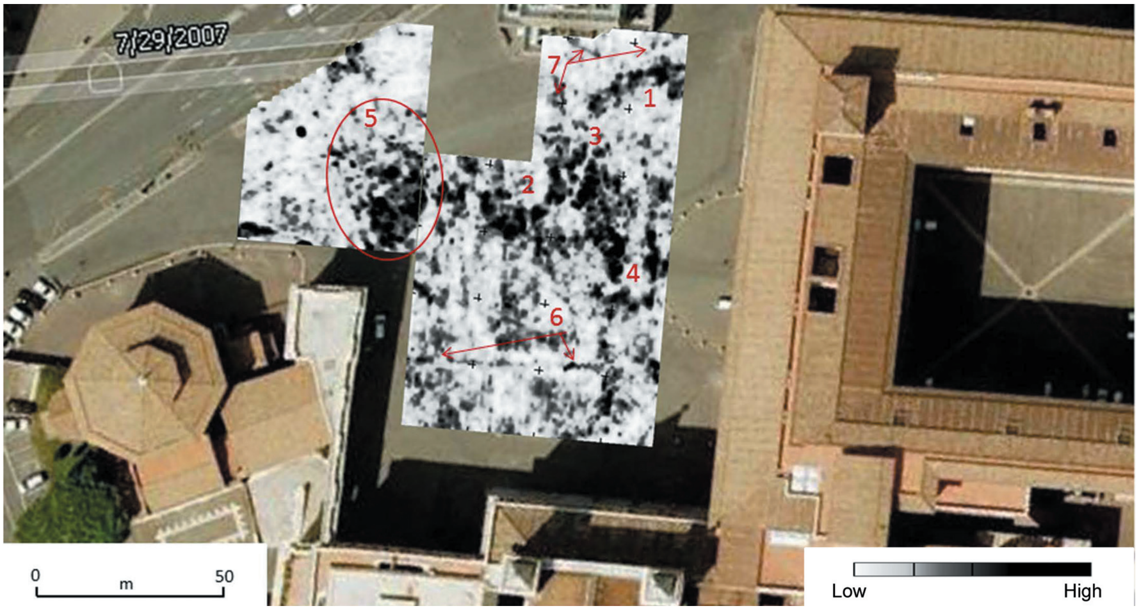

Fig. 5 - St. John Lateran square. Area A1 and B1, GPR 400 MHz, slices at the estimated depth of 0.88 m.

Fig. 6 shows the anomalies located at the estimated depth of 1.75 m [41-45 ns, (twt)], individuated in the area A1 and B1. At this depth the anomalies are confirmed in term of location and size, but with reduced intensity. The size of the anomalies, indicated below, are approximate: (1) this anomaly is still present with dimension of x: 19.50 m, y: 3.00 m; (2) this anomaly is still present with an average dimension of 230 m^2; (5) the corresponding anomaly is present with dimension of 125 m^2; (8) two parallel anomalies, with the same dimension x: 1.70 m, y: 3.00 m; (9) two new anomalies with an average surface of 30 m^2.

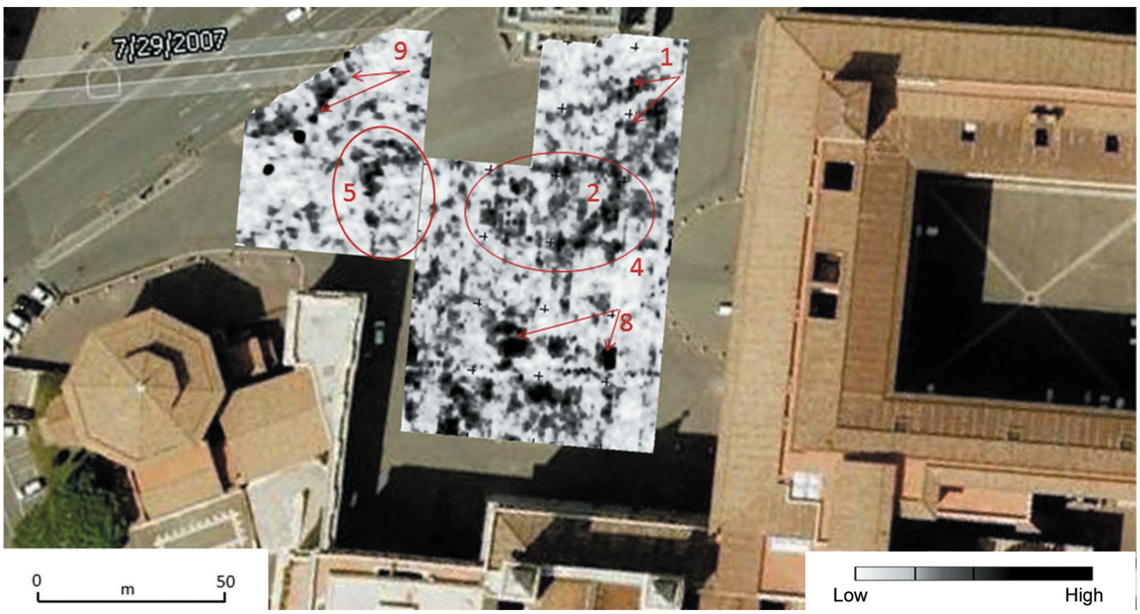

Fig. 6 - St. John Lateran square. Area A1 and B1 GPR 400 MHz, slices at the estimated depth of 1.75 m.

Fig. 7 shows the anomalies located at the estimated depth of 1.35 m [30-34 ns, (twt)], individuated in the area A2, B2 and C2. At this depth, the area is characterized by many strong reflections due to the presence of utilities (1) and of portion of structures (2-3-4-5-6-7).

The size of the anomalies, indicated below, are approximate: (1) these anomalies are due to the presence of utilities (pipes and gully-holes); (2) and (3) must be considered together, they are characterised by structures located perpendicular each other inside a total surface of 960 m^2. In correspondence of anomaly (3) a sequence of squared anomalies at a distance of 1.00 m each other are visible; (4) linear anomaly with low intensity x: 40.40 m, y: 2.00 m; (5) anomaly with a squared shape with dimension 3.70 x 4.50 m; (6) anomaly with average dimension 2.30 x 4.20 m; (7) this zone is characterised by small anomalies.

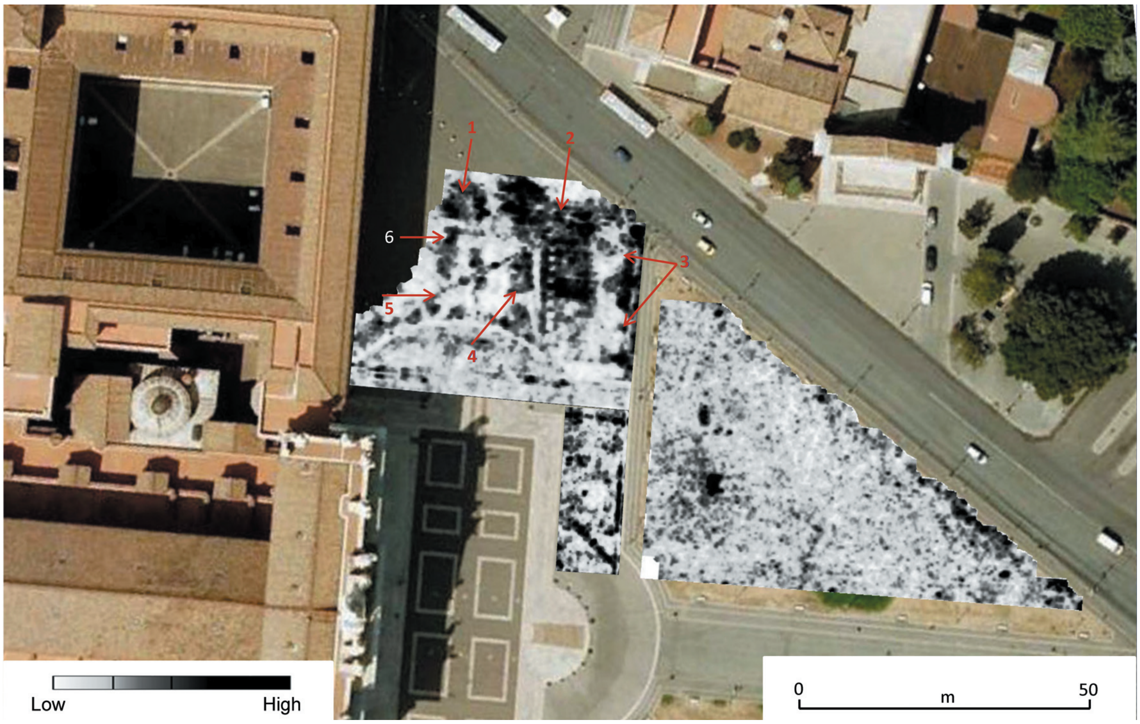

Fig. 7 - St. John Lateran square. Area A2, B2 and C2, GPR 400 MHz, slices at the estimated depth of 1.35 m.

The GPR image is characterized by the presence of structures with different dimension and geometrical shapes. At this estimated depth, squared blocks, among them contiguous, arranged in the L shape with an angle of 90° and with an average surface of 130 m^2, are visible. Between these, the southern structure with rectangular shape is of particular shape. This is characterized along the left side by a sequence of small squared rooms with average dimension of 1.2×1.2 m. In front of the rectangular structure, two semi-circular anomalies, with angular opening of 180° and diameter of 10 m are visible.

Fig. 8 shows the anomalies located at the estimated depth of 2.00 m [47-50 ns, (twt)], individuated in the area A2, B2 and C2. At this depth, the area is characterized by many strong reflections due to the presence of utilities (1) and of portion of structures (2-5-8-9).

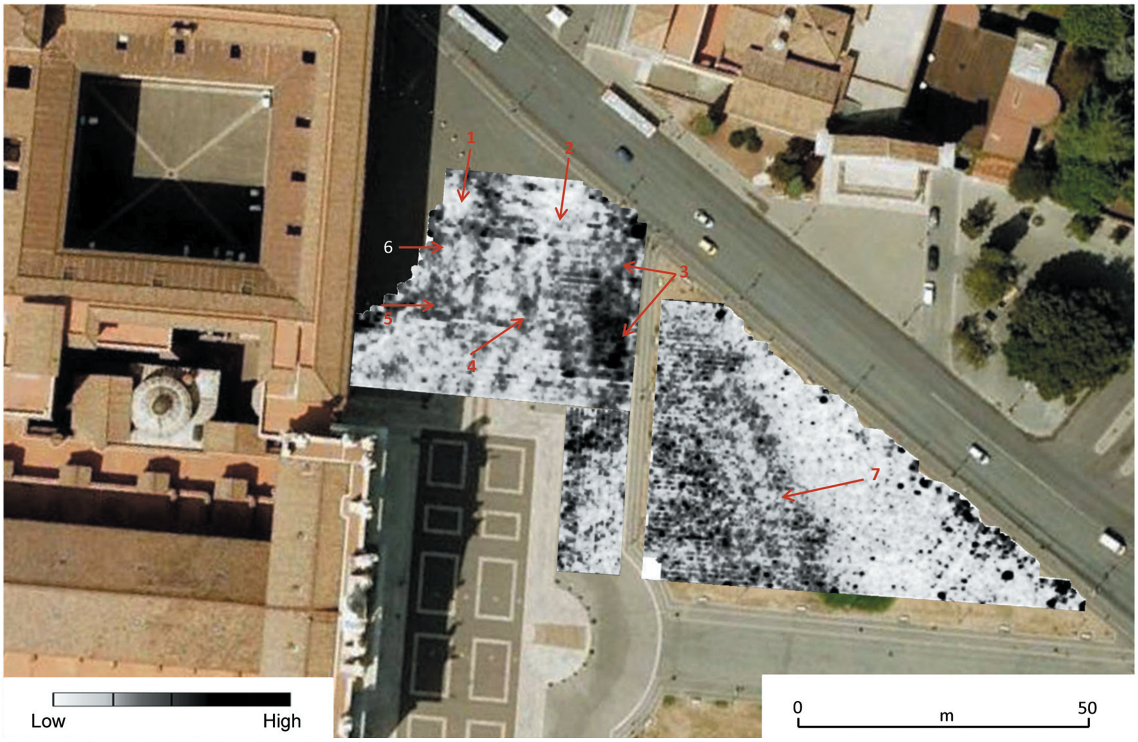

Fig. 8 - St. John Lateran square. Area A2, B2 and C2, GPR 400 MHz, slices at the estimated depth of 2.00 m.

The size of the anomalies, indicated below, are approximate: (1) these anomalies are related only to gully-holes; (2) the traces of the corresponding anomalies are still present; (3) three anomalies with perpendicular orientation, with an average dimension of x: 16.0 m, y: 1.7 m; there are also two anomalies with dimension x: 2.0 m, y: 22.7 m; (5) and (6) these areas are characterised by small reflections; (7) this zone is characterised by diffused anomalies which can be due to the presence of collapse of structures and changing of topographical layer in the ground. The light grey area is characterised by attenuated reflected signals corresponding to a portion of subsoil with high attenuation.

5.2. St. John Lateran square - area A1 and B1 (antenna 70 MHz)

The GPR amplitude maps, related to the profiles collected with 70 MHz antenna have been analysed and our attention has been focused to the following time-windows: 35-42, 47-53, 59-65, 71-77, 89-95 and 112-118 ns (twt), corresponding to the averaged estimated depths of 1.7, 2.1, 2.6, 3.0, 3.8, and 4.7 m, respectively.

Fig. 9 shows the anomalies located at the estimated depth of 6.00 m. At this depth, the area is characterized by anomalies contained in two sectors.

The size of the anomalies, indicated below, are approximate: (1) is characterised (portion visible) by dimension x: 1.4 m, y: 13.0 m and x: 1.4 m, y: 10.0 m; (2) is characterised by dimension (portion visible) x: 17.0 m, y: 3.5 m.

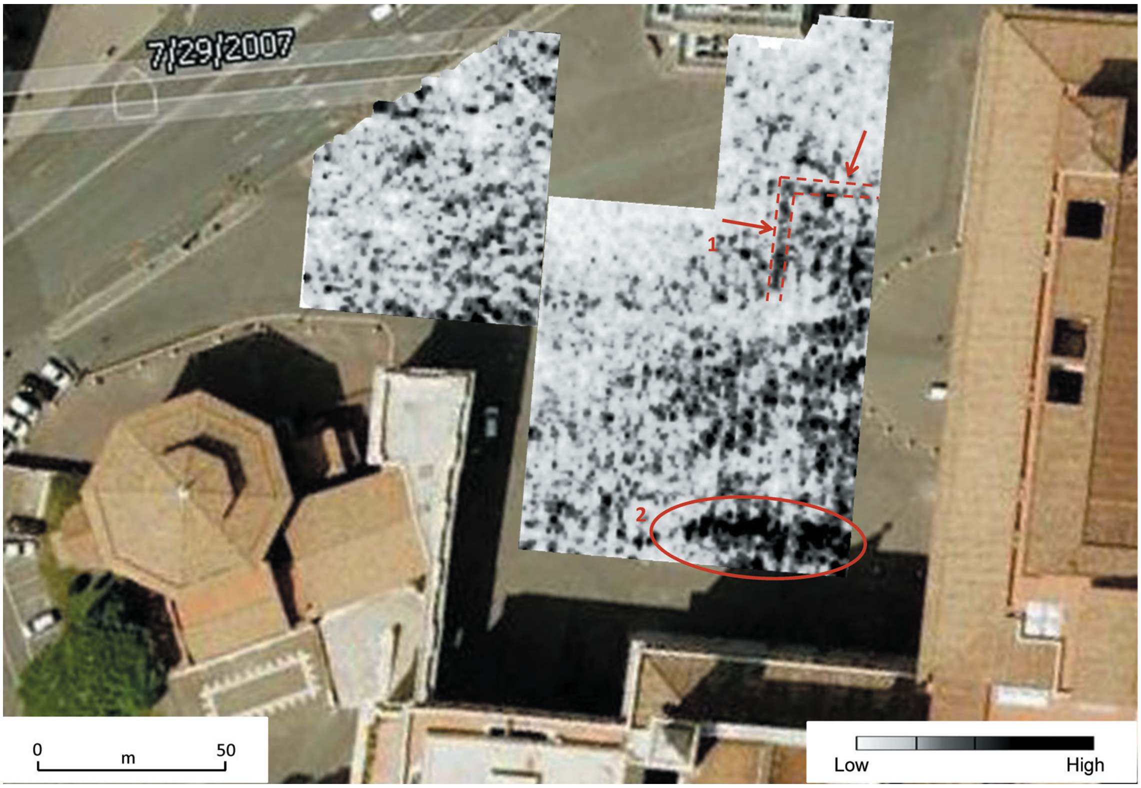

Fig. 9 - St. John Lateran square. Area A1 and B1, GPR 70 MHz, slices at the estimated depth of 6.00 m.

5.3 Results of the survey inside the Basilica

The surface inside the Basilica has been subdivided in 8 different sectors as indicated in Fig. 10. The GPR surveys have been made during January 2016, employing the same GPR system equipped with 400 MHz antenna.

Time slice data sets were generated by spatially averaging the squared wave amplitudes of radar reflections in the horizontal as well as the vertical direction. The squared amplitudes were averaged horizontally every 0.25 m along the reflection profiles 4 ns (for 400 MHz antenna) time windows (with a 5% overlapping of each slice). The resampled amplitudes were gridded using the inverse distance algorithm with a search radius of 0.75 m.

The GPR amplitude maps, related to the profiles collected with 400 MHz antenna have been analysed and our attention has been focused to the following time-windows: 3-7, 10-14, 17-21, 24-28, 38-42, 52-56, 59-63, 66-70, 73-77, 80-84, 87-91 and 94-97 ns (twt), corresponding to the averaged estimated depths of 0.4, 0.7, 1.0, 1.4, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 5.5 m, respectively.

Fig. 10 shows the anomalies located at the estimated depth of 2.00 m [38-42 ns, (twt)], individuated in the area inside the Basilica. At this depth, the area is characterized by many strong reflections due to the presence of portion of different structures.

The size of the anomalies, indicated below, are approximate: (a1) linear anomalies, with dimensions 1 x 4 m, related to the Borromini's works; (a2) this area has been characterised by previous excavations and the individuated anomalies are due to the modern support of the

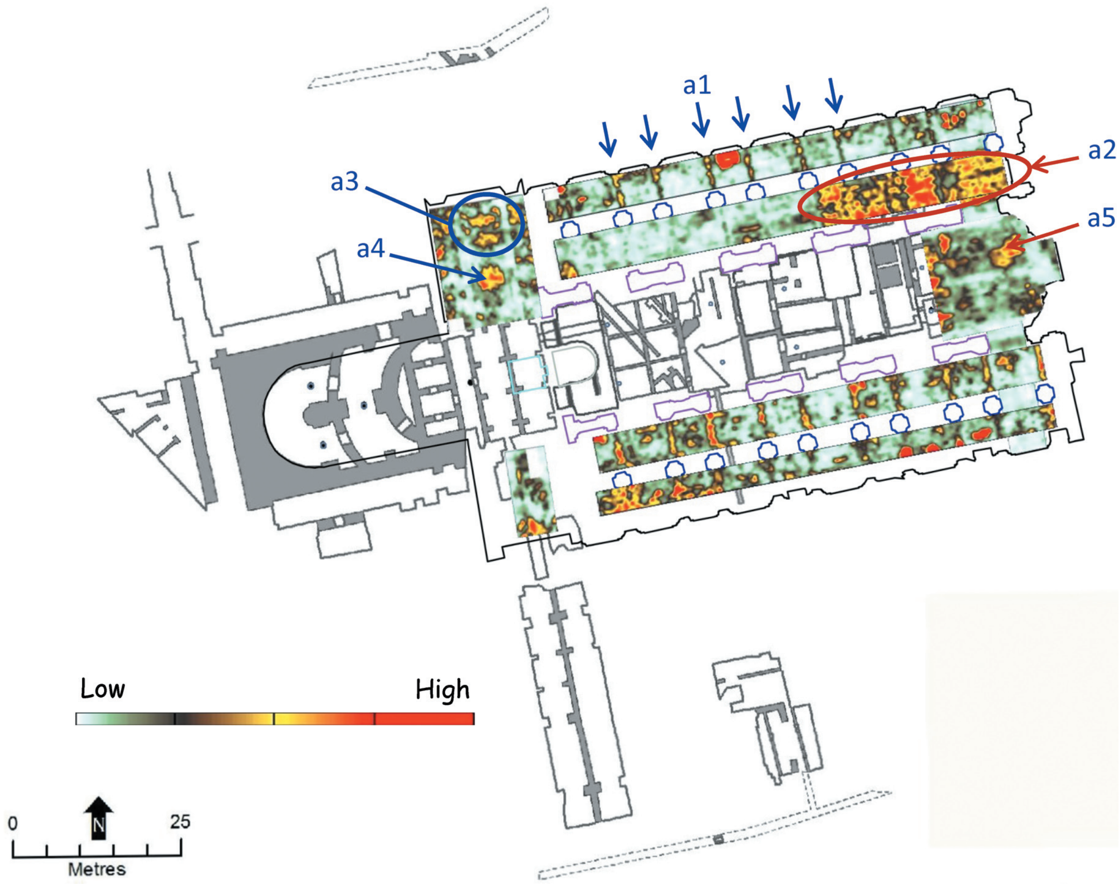

Fig. 10 - St. John Lateran Basilica. GPR 400 MHz, slices at the estimated depth of 2.00 m.

pavement and to the structures still present in the ground; (a3) two anomalies with an average dimension of x: 4 m, y: 1.6 m; (a4) isolated anomaly with dimension of 4.3×3.5 m and (a5) anomaly with dimension of 4.7 x 3.4 m.

Fig. 11 shows the anomalies located at the estimated depth of 4.20 m [80-84 ns, (twt)], individuated in the area inside the Basilica. At this depth, the area are characterized by many strong reflections due to the presence of portion of different structures.

The size of the anomalies, indicated below, are approximate: (a2) this area shows few linear anomalies related to the structures still present in the ground; (a3) two anomalies, at this depth with perpendicular orientation each other and with an average dimension of x: 4.3 m, y: 1.6 m and 1.7×4.7 m; (a5) together with the individuated anomaly it is present a second anomaly with dimension 1.6×10.8 m and (a6) anomaly with dimension of 1.6×3.0 m.

6. Conclusion

GPR surveys at the Lateran have produced significant and fruitful results. The use of 400 and 70 MHz antenna have enabled to reach depths of up to 3.4 and 6.7 m, respectively, in the external area of Basilica.

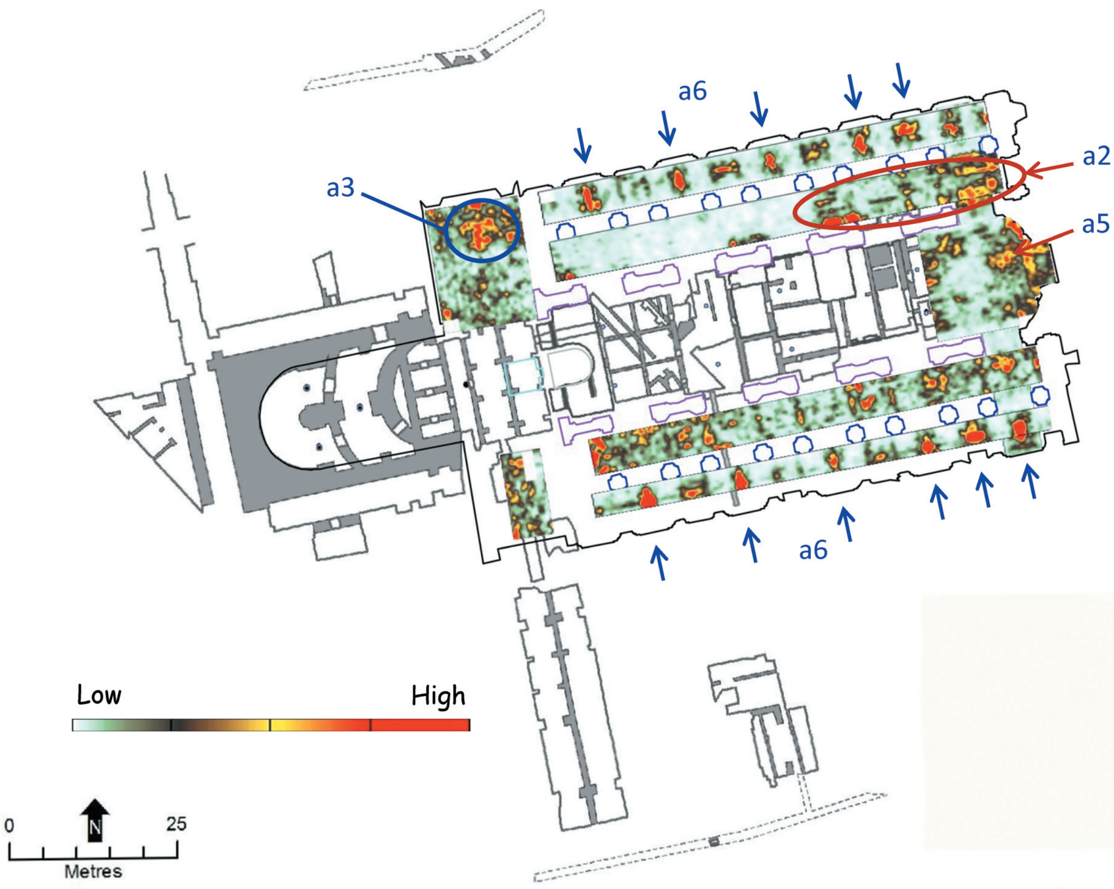

Fig. 11 - St. John Lateran Basilica. GPR 400 MHz, slices at the estimated depth of 4.20 m.

The location, depth, shape and size of buried buildings were determined using GPR, which can be then integrated with the results obtained with the other employed methods.

Taking into account the different aims of the investigations and the obtained results it is possible to observe that in the area A1 the anomalies, located in the depth interval 0.80 - 2.00 m with the 400 MHz antenna (Figs. 4 to 7), can be due to structures related to the medieval age; while the anomaly located with 70 MHz antenna (Fig. 9) presents a good correspondence with the expected direction of the external wall of the *Castra*.

In the eastern part of the basilica area A2, the located anomalies, characterised by many regular and interesting shapes, can be due to the remains of the barracks of the imperial horse guards.

The results obtained inside the basilica have helped the archaeologists to recognize the reinforcements made with Borromini's works (Fig. 10) and few indication through anomaly a3 (Fig. 10) of the remains of the external wall of the first Costantine Basilica.

The present project is still in progress and new surveys have been planned below the actual level and in the eastern part of the basilica.

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