The Impact of High Resolution Ground-Penetrating Radar Survey on Understanding Roman Towns: case studies from Falerii Novi and Interamna Lirenas (Lazio, Italy)

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***Abstract*—In three field seasons, the Roman towns Falerii Novi and Interamna Lirenas (Lazio, Italy) were surveyed using ground-penetrating radar (GPR). The aim was to take maximum advantage of the high resolution capability of the GPR technique. Beside the choice of the antenna frequency, unaliased data recording is important when undertaking a full-resolution GPR survey. In this project, the use of a GPR array allowed a high sample density (~0.05 m in in-line direction, and ~0.06 m in cross-line direction). The accuracy and precision of the positioning by means of an RTK GNSS and a robotic total station nearly fulfilled the requirement that the accuracy and precision should be better than half the required sample density (in this case ~0.04 m). The data were 3D migrated, which improves the lateral resolution. The results of the survey contributed to the understanding of the investigated Roman towns and their early development. For example, private houses, revealed in detail, confirm the existence of a regular pattern of land allotment.**

Keywords—Ground-penetrating radar (GPR), unaliased survey, positioning accuracy, 3D migration, archaeological interpretation, Roman urban survey, non-invasive archaeology

I. INTRODUCTION

As part of the “Beneath the surface of Roman republican cities” project, which started in 2015, a full-coverage ground-penetrating radar (GPR) survey was conducted of two Roman towns in Lazio (Falerii Novi and Interamna Lirenas), which are important for understanding the development of urbanism in Roman Italy. GPR is based on the reflection of radio waves at transitions between materials with a different dielectric permittivity ε (in soils, ε is strongly affected by the moisture content). The amplitudes and travel times of the reflected waves are measured, resulting in vertical radargrams. Combining many parallel radargrams allows extracting horizontal slices at different depths [1].

Beside the capacity to produce 3D data, GPR can also provide information with a higher resolution than most other geophysical techniques used in archaeology. Therefore the aim of the investigations at Falerii Novi and Interamna Lirenas was to take maximal advantage of the high-resolution capacity of the GPR technique (‘full-resolution’ GPR imaging), in order to understand the origins and early development of these two Roman towns. To do this, an appropriate survey methodology is needed. The choice of the antenna frequency affects the vertical and horizontal resolution, and the interpretability of smaller figures. The sample density is also essential for a reliable interpretation: a full-resolution GPR survey requires unaliased data recording [2]. Furthermore, the data need appropriate processing before they can be interpreted in a meaningful way.

After a brief description of the two Roman towns investigated, we discuss these theoretical requirements, and we indicate how and to which extent our survey has fulfilled them. We then present some results, and show how the archaeological understanding of Falerii Novi and Interamna Lirenas has benefited from the high-resolution GPR surveys carried out within this project.

II. FALERII NOVI AND INTERAMNA LIRENAS

A. *Falerii Novi*

Falerii Novi, situated about 50 km north of Rome (Fig. 1), near Civita Castellana, was founded in the 241 BC, after the defeat of the Faliscan revolt. The exact nature of the town has remained uncertain. Owing to the lack of recent development, the site, covering an area of 30.6 ha, lies in open fields occupied only by a church and a former monastery, now used as a farm. It is surrounded by an impressive republican town wall. Falerii Novi has seen little excavation, with the exception of work in the early 19th century and a large trench excavated in the 1960s. As a consequence, our evidence for the town comes almost exclusively from non-invasive methods. In the 1990s, a fluxgate gradiometer survey led by Simon Keay and Martin Millett with the British School produced the first complete plan of a Roman town in Italy [3]. It revealed the overall layout of the town and the original street grid, and suggested how this original plan subsequently expanded up to the town walls. The survey also revealed a series of temples around the periphery of the town [4]. A fluxgate gradiometer survey of the area immediately outside the walls on the northern side of Falerii Novi was undertaken between 2002 and 2008 [5].

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Fig. 1. Location of the two investigated Roman towns

B. *Interamna Lirenas*

Interamna Lirenas is situated in the Liri valley, about 100 km south of Rome (Fig. 1), near Cassino. It was founded as a Latin colony in 312 BC, following the Roman conquest of the area, and abandoned probably in the second half of the 6th century [6]. Today the site is used as agricultural field, on a ridge between two streams, with the course of the Roman Via Latina running along its axis. Unlike Falerii Novi, there are only a few poorly preserved structural remains visible above ground. There has been little past archaeological investigation, except for a Canadian field survey led by Edith M. Wightman. In 2010, the University of Cambridge started an investigation aimed at exploring the long-term development of the town and its hinterland, in collaboration with the Soprintendenza. It involved a fluxgate gradiometer survey of the complete town (2010–2012, see [7]), systematic surface sampling and test pitting of the ploughsoil, and the excavation of the roofed theater [8], identified during a pilot GPR survey undertaken by the British School at Rome in 2012–2013 [7].

III. METHODOLOGY OF THE GPR SURVEY

A. *Data acquisition*

1) Transect spacing: Data were collected in three field seasons (2015–2017). A total area of 49.1 ha was covered (26.6 ha at Falerii Novi, and 22.5 ha at Interamna Lirenas). We used a Sensors & Software Spidar GPR network, comprising fifteen single antennas with a center frequency of 500 MHz. This frequency has proven to be effective for the prospection of Roman urban sites, see e.g. [9,10]. The antennas were mounted onto a wooden cart towed by an all-terrain vehicle (ATV). Since the width of one antenna housing is ~0.25 m, arranging the antennas in two rows (of eight and seven antennas), offset with respect to one another, resulted in a profile spacing of 0.125 m (Fig. 2).

The transformation of representative profiles into the frequency-wavenumber domain [10] resulted in a maximum spatial frequency of ~6 m^{-1} for a temporal frequency of ~450 MHz. Hence the maximum sample interval for unaliased data collection was approximately 0.083 m. As a consequence, the profile spacing of 0.125 m did not fully meet the requirements for an unaliased GPR survey allowing to achieve maximum resolution. Therefore a second pass was made to reduce the transect spacing further to 0.0625 m (Fig. 2). Readings were taken every 0.05 m along the transects.

2) Positioning accuracy and precision: For an unaliased survey, position accuracy and precision should be better than half the required sample density, in order to unambiguously assign each GPR measurement to the correct grid position [2,11]. When we apply this to the surveys carried out at Falerii Novi and Interamna Lirenas, positioning precision should be better than 0.042 m. We acquired position data with a Leica GS15 real time kinematic (RTK) GNSS instrument, which received corrections from reference stations via mobile internet. Of our GNSS measurements, ~85 % had a 3D coordinate quality (CQ) better than 0.02 m. The 3D CQ is calculated such that there is at least a two third probability that the computed position deviates from the true position by less than the CQ value [12]. In areas where the GNSS readings were not precise enough (because of a low number of satellites when measuring under trees, or because the mobile internet connection was interrupted), a Leica TS 15 3” robotic total station was used.

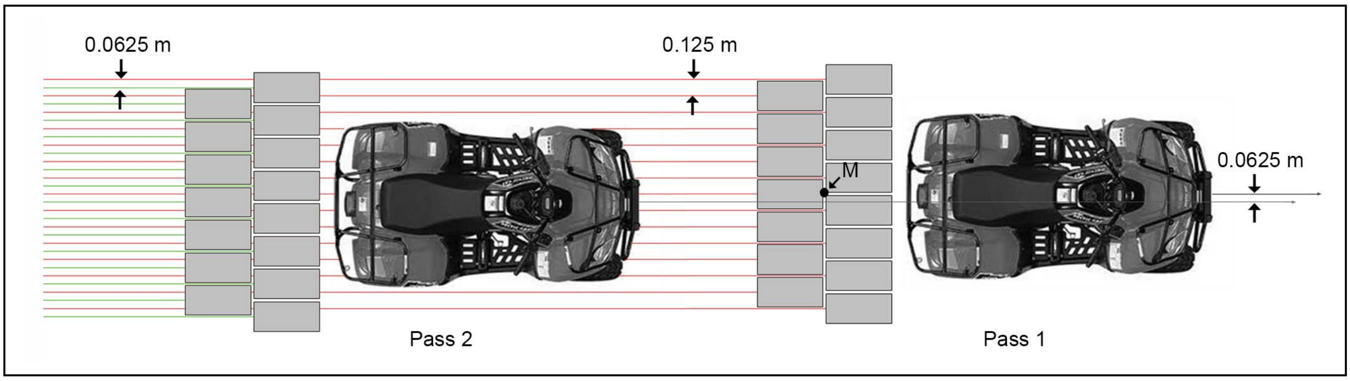

Fig. 2. Recording scheme used during the GPR surveys at Falerii Novi and Interamna Lirenas. The antennas were mounted in two rows so that the spacing between the profiles is 0.125 m (red lines). Two passes were made, following theoretical lines with a distance of 0.0625 m between them (grey lines). The second pass allowed further reducing the transect spacing to 0.0625 m (green lines). M = theoretical midpoint of the array.

In tracking mode, the accuracy of its distance measurements is 0.003 m + 1.5 ppm, and the accuracy of the angular measurements is 1 mgon [13]. For the distances measured during the GPR surveys (< 200 m), this results in a 3D CQ usually better than 0.005 m [12]. Since the total station was set up by means of a resection using multiple GNSS points, the 3D CQ of the GNSS and of the total station should be added when assessing the accuracy of the total station measurements.

Another important factor in the quality assessment of the positioning data is how closely the theoretical transects were followed by the GPR operator during data acquisition. As described, the GPR surveys at Falerii Novi and Interamna Lirenas were conducted with single antennas in parallel, fixed onto the cart so that the cross-line spacing between the antenna midpoints was 0.125 m. During the second pass, made to further reduce the cross-line spacing, profiles had to be acquired between the previously recorded ones (Fig. 2). Therefore it was crucial that the theoretical path was followed closely when driving the ATV. The coordinates measured by the RTK GNSS or total station were fed into a navigation system guiding the driver so that the desired trajectory was followed as closely as possible. The root-mean-square operator error (i.e., the distance between the location of a theoretical grid point, and the location of the closest measurement actually taken) was 0.029 m (0.014 m in in-line direction and 0.026 m in cross-line direction).

Coordinate accuracy is also affected by latency (the time delay between the position measurement and its fusion with the GPR data). Because of the low speed of the ATV (~0.5 m/s) in order not to damage the GPR sensors when stones lie at the surface, it can be assumed that latency had only a small influence. The total positioning accuracy (the accuracy of the GNSS and total station measurements, and the accuracy when driving the ATV) in in-line and cross-line direction can thus be estimated not to exceed 0.06 m. This nearly fulfils the criterion described above (0.042 m).

3) Attenuation of the GPR signal by soil moisture: In soils with higher conductivity, GPR waves can be attenuated. The large contribution of the moisture content to the soil conductivity is illustrated in Fig. 3, which shows a small part of the GPR survey results from Interamna Lirenas. The measurements in Fig. 3a were conducted on 23 July 2016, when the soil was very dry after a long period without rain. The same area was surveyed again on 31 July, after five days of rain (24–28 July) and two dry days (29–30 July). A deterioration of the signal-to-noise ratio is visible: the noise stripes in the direction of the survey lines are stronger, and some building traces are less clear or absent in the data set collected in soil with a higher moisture content (Fig. 3b). Further tests demonstrated that it was optimal to wait three to seven days for the ground to be dry enough before continuing the survey, depending on the amount of rain.

4) GPR antenna height: The radiation pattern emitted by GPR antennas is dependent on their elevation above the surface. Simulations [14] showed that as a dipole antenna is raised 0.05 m, the amplitude decreases. This effect is more significant when the antenna height is 0.20 m. Moreover, the radiation pattern becomes more directional. Because of this higher directivity, the horizontal spatial bandwidth decreases, and therefore also the horizontal resolution. These calculations correspond well with the results of field tests comparing an air-launched and a ground-coupled stepped-frequency continuous wave GPR array [15].

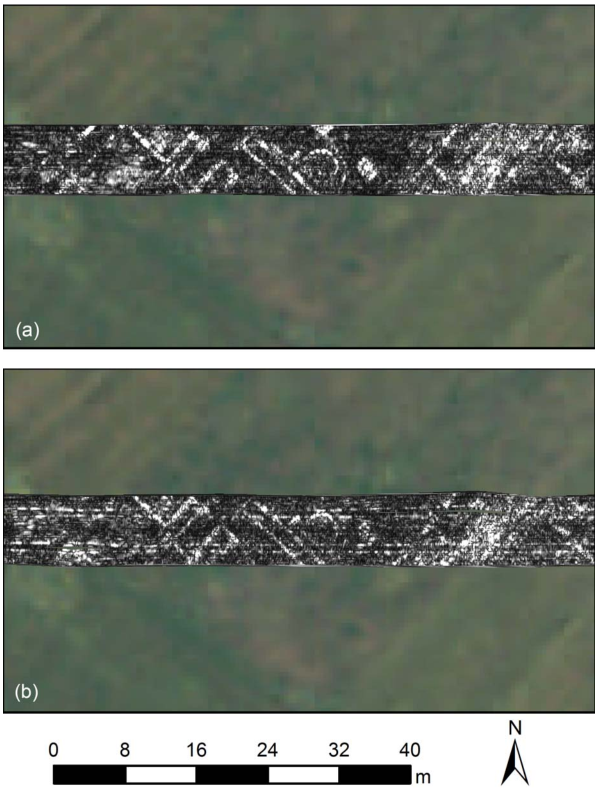

Fig. 3. Time slices from Interamna Lirenas, at an estimated depth of 0.55–0.60 m, showing wall fourndations. (a) After a long period of drought. (b) After five days of rainfall, the signal-to-noise ratio has deteriorated because of the attenuation of the GPR waves.

Especially over more conductive soils, the ground-coupled array produced a better signal-to-noise ratio in the deeper reflections, and longer diffraction tails indicating a wider antenna radiation pattern and a higher spatial resolution. At Falerii Novi, we compared the response of the Spidar system when the antennas were resting on the surface, with the results for an antenna height of 0.20 m. Of the archaeological features visible in the data set collected with zero antenna height, only few could be detected when the height was increased to 0.20 m. Therefore, despite some advantages (an easier use on uneven terrain and the absence of artefacts due to ground-coupling difficulties), the reduced depth of penetration prevented the use of air-coupled antennas. This conclusion warranted the work carried out to prepare the fields in order to ensure the best possible contact of the sensors with the surface: the vegetation was cut short and stones, fragments of roof tiles and other debris were removed. At Falerii Novi, this occurred mainly manually, a laborious process. At Interamna Lirenas, a different method was adopted, using a road roller to push stones into the topsoil after the vegetation had been cut.

B. Data processing

After the elimination of the low-frequency component in the signal (dewow, using a window of 4 ns), time zero was aligned. This occurred automatically through the selection of a trace from the profile, and the computation of the cross-correlation of this trace (the template) and each individual trace in the profile. The traces were then shifted upward or downward, based on the amount of shift that yielded the highest cross-correlation. The smallest increment for the shifting was 1/10 of a temporal sample (0.02 ns). Time zero was then set at the zero amplitude point before the first positive peak. The same gain function was applied to all traces to enhance later arrivals and preserve relative amplitudes. It was based on the inverse average envelope of the amplitude of all traces, smoothed using a moving average filter with a length of 3 ns. Furthermore, a low-pass frequency filter (1 GHz) was applied.

The GNSS receiver or the total station prism were mounted above the theoretical midpoint (M) of the array (Fig. 2). The coordinates of the antennas were calculated taking into account the direction of the array, which was determined by looking at the two nearest surrounding coordinates of M, and the known distance of the individual antenna midpoints from M both in in-line and cross-line direction. The GNSS receiver allowed a coordinate acquisition with a frequency of 20 Hz, so that the position was known for each GPR trace. When the total station was used, the acquisition frequency was < 5 Hz, so that the position was not available for each GPR trace. To the intermediate traces, coordinates were assigned by linear interpolation between the two nearest available total station measurements. Horizontal slices were produced by interpolating the data onto a regular grid of 0.05 m × 0.05 m using Delaunay triangulation, involving linear interpolation between the amplitudes at the corners of the triangle surrounding the grid point.

In the profiles, considerable banding was visible. Background removal (the subtraction of the average of all traces in a profile from each individual trace) did not entirely remove stripes in the time-slices, caused by variations in the amplitudes recorded by the different channels in the network. These were more adequately suppressed by calculating the average of the data recorded by each channel within a swath, and equalizing these average values. This process was repeated for each temporal sample.

TABLE I. AVERAGE GPR WAVE VELOCITY FOR DIFFERENT TWO-WAY TRAVEL TIMES AT THE TWO INVESTIGATED SITES

Two-way travel time (ns)	**Velocity (m/ns)**	
	Falerii Novi	***Interamna Lirenas***
10	0.097	0.091
35	0.070	0.072

Migration velocity analysis (MVA), performed at 550 locations (275 at each investigated site), resulted in a nearly identical average wave velocity at both sites (0.087 m/ns at Falerii Novi, and 0.086 m/ns at Interamna Lirenas). When a linear polynomial is fitted to the MVA results, the velocity can be shown to decrease with increasing two-way travel time (TWTT; Table 1). There is also a lateral velocity variation: the standard deviation of the velocities at a particular TWTT is usually around 0.01 m/ns. Using the obtained GPR wave velocities, the data were migrated with a 3D phase-shift algorithm [16]. Beside data recording in a dense grid, migration improves the lateral resolution. It collapses diffractions, moving reflections to their correct location at the apex of the hyperbola, and it removes out-of-plane reflections [2]. This is illustrated in Fig. 4, a time-slice showing the eastern part of the theater at Falerii Novi. After migration, the boundaries of several features are sharper. An example is the curved structure marking the transition between the *orchestra* (the semi-circular central part of the theatre) and the lower *cavea* or seating area. Also the edges of the radial walls supporting the upper *cavea* are clearer. Although their thickness varies, we can estimate that these walls were ~1.25 m thick.

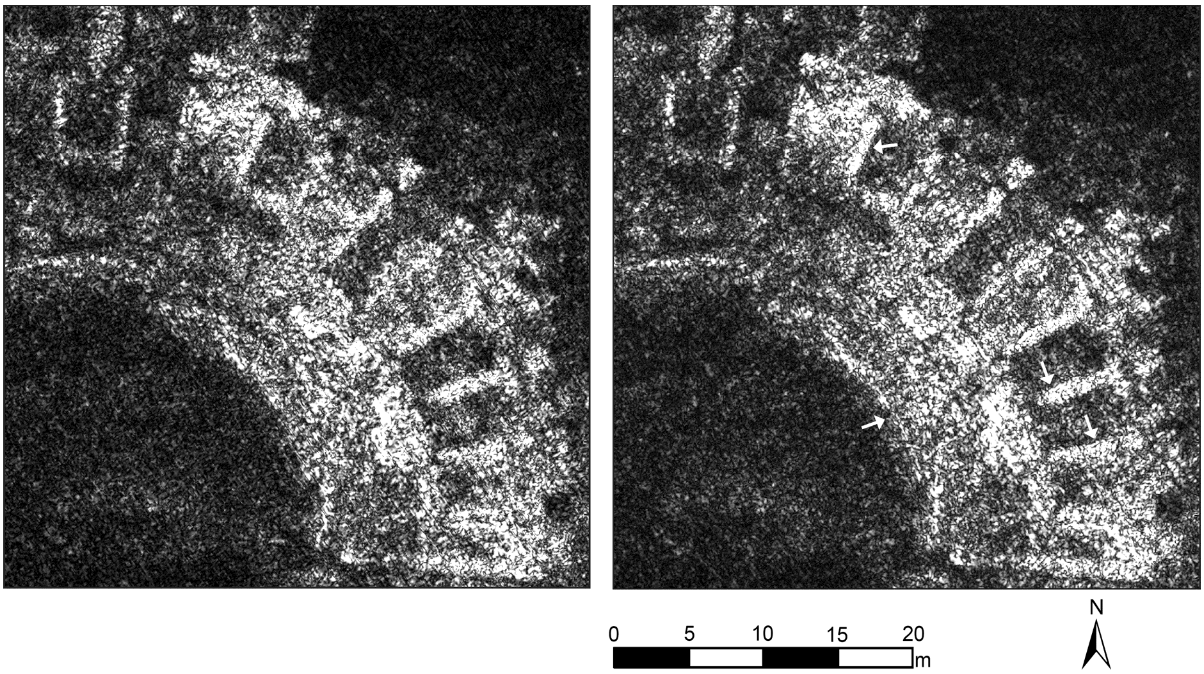

Fig. 4. GPR time slice between 22 and 23 ns (corresponding to a depth of approximately 0.85–0.90 m) from Falerii Novi, showing the eastern part of the theater. Of several structures, the edges are sharper in the image after 3D migration (right), especially near the arrows.

So far, conventional elevation static corrections have been applied to the GPR data. In general, topographic relief was moderate at the two investigated sites. At Interamna Lirenas, there are strong undulations near the boundaries of the survey area with maximum surface gradients of ~23 %, although in these areas no archaeological traces were detected by the GPR. At Falerii Novi, the gradient exceeded 10 % in a few locations. A gradient of ~15 % occurred for example in the theater area (Fig. 4), which is still visible in the topography. If there are strong undulations in the topography (>10 %), conventional methods are not sufficient for correcting the GPR data for the topography. Topographic migration [17,18] will be applied to correct the data collected in areas where the acquisition surface was very uneven.

IV. RESULTS AND ARCHAEOLOGICAL INTERPRETATION

In the previous section, it was described how the GPR surveys at Falerii Novi and Interamna Lirenas attempted to achieve maximum resolution through a high sample density allowing unaliased data recording, and by applying 3D migration. How this high resolution can contribute to the understanding of these towns and Roman urban centers in general, becomes clear when the domestic buildings in the GPR data are analyzed. At Falerii Novi, the fluxgate gradiometer survey conducted in the 1990s demonstrated that the town was densely occupied, with a number of public buildings surrounded by private houses. Most of the larger houses were found in the *insulae* at the center of Falerii Novi, and are oriented east-west. This led Keay *et al.* to suggest that an original, regular pattern of land allotment could be discerned [3]. This can now be confirmed on the basis of the GPR results, which reveal some of the houses in great detail, especially in the area southwest of the *forum*. Here, individual rooms of the houses can be discerned, through the wave reflections caused by the walls that delimit them, or (more often) through the reflections of the floors, where the walls form negative anomalies (areas without reflections). In this area, the size of the individual parcels appears to be approximately 30 m × 15 m, although, as observed by [3], it is not always straightforward to draw the boundaries of houses since several original parcels may have been combined into a single property at a later date.

Also when it comes to public buildings, GPR and magnetometry data reveal complementary views. At Falerii Novi, the GPR provides evidence for big buildings that were not visible in the fluxgate gradiometer data. Examples are a temple near the south gate, a bath complex with a central octagonal hall, an octagonal *macellum* (market hall) in the western part of the town, and a three-sided portico near the north gate, covering approximately 100 m × 40 m. Also at Interamna Lirenas, the *basilica* and a number of porticoed enclosures were previously unknown. At other locations, the fluxgate gradiometer survey produced a clearer image. For example, at Falerii Novi, the *tabernae* (shops) on the *forum* are more comprehensible in the magnetometer data, whereas they do not show clearly in the GPR results.

This complementary character illustrates the need to compare and combine as many different data sets as possible (geophysical data, but also results from field walking, test pitting or excavations) in order to achieve a reliable archaeological interpretation. One step further than the side-by-side analysis of different data sets is the combination of data to produce a single output image: ‘data integration’ or ‘data fusion’. There are many data integration methods [19,20]. In a simple example from Interamna Lirenas, showing a residential building, a semi-transparent layer containing magnetometer data has been superimposed on a GPR time-slice. The fluxgate gradiometer data (Fig. 5a) show magnetic anomalies of up to ~40 nT. Combination with the GPR data (Fig. 5b), in which the walls or foundations show up more clearly, provides the context of the magnetic anomalies (Fig. 5c). Given the strength of the anomalies, one might interpret them as the result of heating (e.g. a hypocaust), although the excavation of the theater (see below) demonstrated that similar magnetic anomalies were caused by floor surfaces or debris. Indeed, even if they are no longer in the same direction as when they were fired in a kiln, bricks can cause high magnetic readings as the remanent magnetization vector turns toward the direction of the Earth’s magnetic field with time [21].

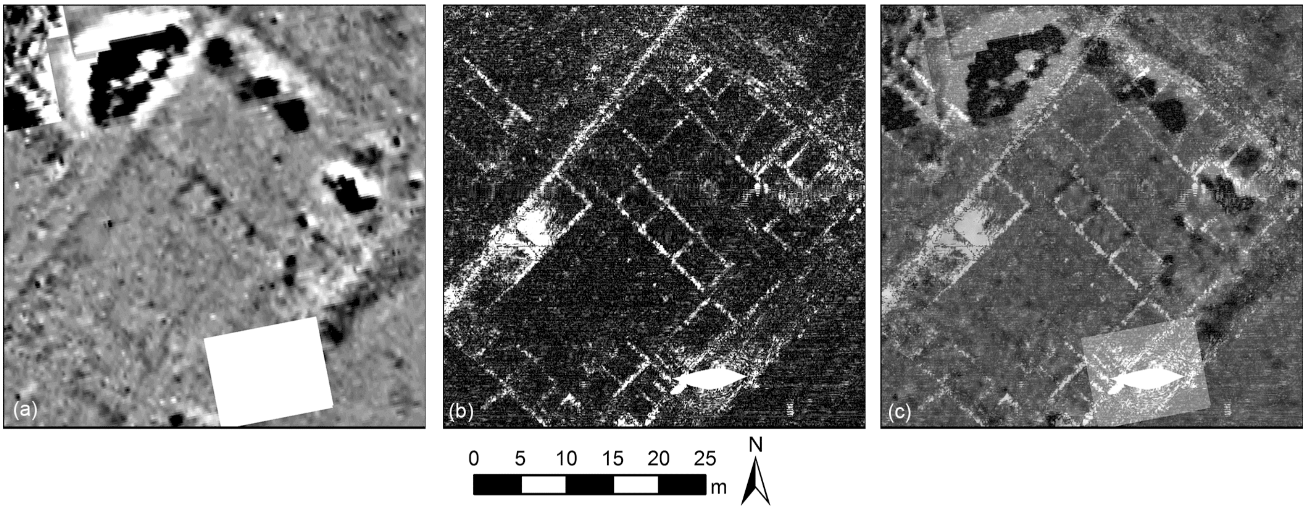

Fig. 5. (a) Fluxgate gradiometer data from Interamna Lirenas, data range: -20 nT (white) to 20 nT (black). (b) GPR time slice between 11 and 12 ns (corresponding to a depth of approximately 0.45–0.50 m). These data show the complementary character of both techniques. Whereas in the GPR data the walls or foundations of a probable residential building are better resolved, the strong magnetic anomalies can give further information on this complex: these could, for example, represent a large quantity of debris. When both data sets are fused (c), this evidence can be assigned to a few specific rooms in the building.

At Interamna Lirenas, the roofed theater (*theatrum tectum* or *odeum*), built in the second half of the 1st century BC [8], has been excavated entirely (2013–2017). This provided an opportunity to assess the GPR wave attenuation and signal penetration depth. Before the excavation, the GPR survey, carried out in 2015, had produced information on the walls supporting the upper part of the *cavea,* and the on the *scaena* wall which forms the background of the *pulpitum* (stage), down to a depth of ~1.8 m. These GPR data corresponded well with the excavation results. However, the lower part of the *cavea* and the wall separating the *pulpitum* from the *orchestra* are absent in the GPR images. We measured the elevation of those excavated structures which in the time-slices correspond with the maximum depth of the GPR signal penetration (e.g., the transition between the lower and upper *cavea*), and compared this with the digital elevation model measured simultaneously with the GPR measurements before the excavation. This comparison showed that structures starting at a depth greater than ~0.75 m had not been detected by the GPR. Although this value is not necessarily valid for the entire towns investigated, it indicates that even during periods of dry weather, such as at the time of the prospection of the theater (July 2015), the attenuation can be considerable. It also raises the question on how to interpret the absence of features in the GPR data (e.g. in the lower areas near the edges of Interamna Lirenas): are these due to a real absence, or to a limited depth of the GPR signal penetration? Further investigations (electrical resistivity imaging, augering, test excavations) can clarify this.

V. CONCLUSION

When the high-resolution capacity of GPR is fully utilized, this technique can provide a wealth of information about Roman towns. At Falerii Novi and Interamna Lirenas, unaliased data acquisition, involving a dense sampling strategy, combined with 3D migration, revealed temples, baths, porticoes, and private houses in great detail. By combining an array of single GPR antennas with accurate, centimeter-precise positioning instruments, a full-coverage survey of both towns became possible, shedding light on their origins and development. Although it was demonstrated that attenuation was important, the GPR prospection was able to pick up relevant structures since these were mostly shallow. As GPR informs only on one physical soil property, combining it with other types of information enhances the interpretative potential. This was illustrated with the fusion of magnetometer and GPR data.

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