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The Roman City of Altinum, Venice Lagoon, from Remote Sensing and Geophysical Prospection

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ABSTRACT Geophysical prospection on 14 ha integrates the processing and interpretation of vertical multispectral and oblique aerial images for uncovering the archaeology of the Roman city of Altinum. This Iron Age and Roman harbour city was completely abandoned in the early Middle Ages, when people moved to nearby lagoon islands, and so the site is particularly fit for the application of non-invasive techniques. Primary aims of the research were to test the interpretation of archaeological structures in the city centre, estimate their degree of preservation in the subsoil, and update previous knowledge on the urban landscape. Target areas were identified first through remote sensing with later magnetic gradiometer mapping of the consular road (via Annia) and its adjoining streets, foundations of large buildings, theatres, temple and forum, a main canal with possible boatyard/storing place and workshops. Multi-electrode automatic resistivity profile produced a very detailed survey of the little theatre (odeon) and basilica. The ground-penetrating radar traced the city walls, while frequency-domain electromagnetics mapped the street pattern.
Buried archaeological structures were located with an estimated error < 0.5 m. Floors and foundations of Roman buildings and infrastructures appear to be preserved between 0.5 and 2 m depth. They probably relate to a reorganization of the city, which occurred between the second half of the second century and the end of the first century BC, having via Annia and the forum as the main city axis, and incorporating few elements of the Iron Age settlement, such as the canal and city boundary. Eight city districts could be recognized, each one showing prevalent public, residential and other productive functions. In the ancient past the monumental buildings of the city were potentially visible from ships in the Adriatic Sea, and could act as nautical signals of the entrance to the lagoon along this low and otherwise monotonous coast. Copyright © 2015 John Wiley & Sons, Ltd.

Key words: Remote sensing; geophysical prospection; Roman Empire; topography of ancient towns; northern Italy; Venice Lagoon

Introduction

The exploration for and mapping of buried archaeological features using technologies that leave the structures untouched in the ground, represents the cutting-edge frontier of field archaeology (Campana and Piro, 2009; Conyers and Leckebusch, 2010; Vermeulen *et al.*, 2012; Johnson and Millett, 2012; Lasaponara and Masini, 2012; Schmidt, 2013; Corsi *et al.*, 2013). Remote sensing and geophysics have the potential to produce two-dimensional and three-dimensional maps of buried features providing information on the geometry of objects as well as the buried topography (Horsley *et al.*, 2014; Keay *et al.*, 2014; Fassbinder, 2015). These methods can indicate the best location for future excavations in order to understand the stratigraphic framework of buried sites and determine ages of buried features. A drawback of the non-destructive approach is the lower resolution compared to excavations, but modern imaging technology is rapidly filling this gap (Novo *et al.*, 2013). Geophysical prospection has been applied in diverse

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archaeological settings, spanning from large Prehistoric and Protohistoric sites (Conyers *et al.*, 2013; Mele *et al.*, 2013; De Smedt *et al.*, 2014), to Roman military settlements (Drahor *et al.*, 2008; Fassbinder, 2010) and cities (Gaffney *et al.*, 2008; Papadopoulos *et al.*, 2012; Vermeulen, 2012; Boschi, 2012).

Here we present a geophysical analysis of the Roman city of Altinum near Venice, Italy, using multispectral aerial and satellite images, magnetic gradiometer, electrical resistivity, ground-penetrating radar (GPR), and frequency domain electromagnetics (FDEM). The aim of the investigation was to define the three-dimensional geometry and degree of preservation of buried features such as the forum, theatres, temple, city walls, main roads and canals, in order to better understand functions and relationships between public, religious, residential and more productive areas of the city.

Strategically located along the inner margin of the Venice Lagoon (Figure 1), Altinum was a major Iron Age and Roman harbour city, which took full advantage of its central position in the network of trades from the eastern Mediterranean to central Europe (Tirelli, 2011a). It was abandoned between the sixth and the seventh century AD, as its inhabitants sought refuge from warfare and insecurity by moving to the lagoon island of Torcello (De Min, 2000; Ammerman and McClennen, 2001; Calaon, 2014), and others nearby (Traviglia and Cottica, 2011; Gelichi *et al.*, 2012).

Altinum is a unique example of a Roman city in Italy and Europe, as it has not been buried by later buildings and other infrastructures from the Middle Ages until modern times. The ancient city is now farmland that was reclaimed between the nineteenth and early twentieth century. Furthermore, the urban centre has not been the object of extensive archaeological excavations during the last two centuries (Paveggio, 2011), as was the case at most other abandoned cities in Italy and the Mediterranean area (Christie, 2012). The lack of excavations and other construction activity has preserved the archaeological record, which can now be investigated with modern scientific methods.

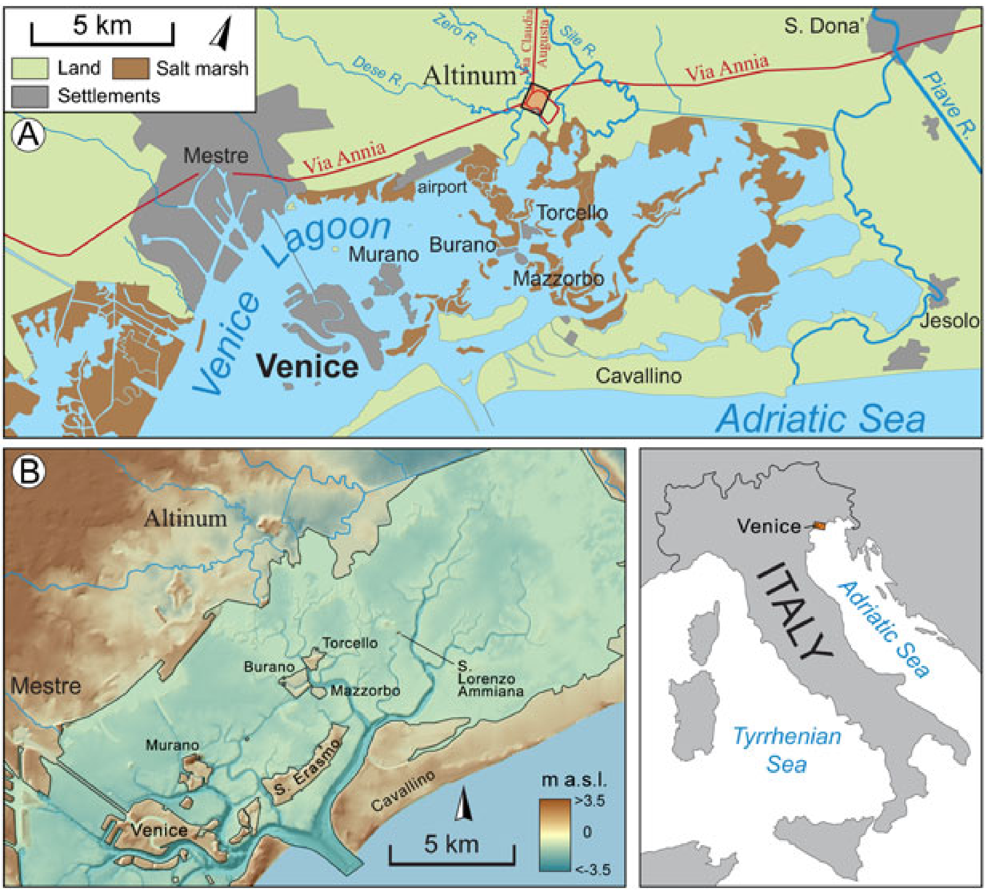

Figure 1. Location of the study area. (A) The city of Altinum, with red lines reporting the urban walls and the major Roman roads; (B) digital elevation model of the eastern sector of Venice Lagoon and its mainland where a topographic mound corresponds to the ancient site. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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Archaeological research in Altinum has produced a wealth of new data on the structure, organization and evolution of a Roman city over a long period of time from the end of the Iron Age to Late Antiquity. Though heavily despoiled during the Middle Ages, processing and interpretation of digital aerial pictures show that the Roman city is well-preserved at shallow depth (Ninfo *et al.*, 2009). The high visibility of buried structures from remote sensing evidences the exceptional preservation of the site (Renfrew and Bahn, 2012). In addition to aerial photographs only a small magnetometric survey had been conducted prior to this research to test the presence of buried streets and wall foundations in an area where information from aerial images was lacking (Veronese, 2000). Using this information we then focused our research on the integration of newly acquired remote sensing images with geophysical investigations in key areas of the city centre.

Another key issue that was focused on relates to Altinum's early colonization along the lagoon. There were Roman settlements at Torcello since the second century AD (Ammerman and McClennen, 2001; Calaon, 2014), and nearby at San Lorenzo di Ammiana since the fourth century AD (Gelichi *et al.*, 2012) (see Figure 1 for location). There probably was a direct and active role by the people from Altinum in the development of the early Medieval settlement of Torcello, which shows several analogies in terms of structure, building materials and environmental setting to the first settlements in Venice around the eighth century AD (Ammerman, 2012). We also carried out investigations along the canal that crossed downtown Altinum, in order to better understand the configuration of its banks and adjoining areas, and to highlight economic significance and role as a waterway to the lagoon.

Settings

Archaeology

Altinum was a major Iron Age city of the so-called Veneti Antichi culture (Gambacurta, 2011a, 2011b). Historical and archaeological sources suggest that the transition under the Roman rule in the area was peaceful, as inhabitants progressively acquired Roman habits and institutions (Cresci Marrone, 2011). In the second century BC Altinum was crossed by the consular road known as via Annia (Veronese, 2009, 2011; Rosada *et al.*, 2010) that connected main towns along the northern Adriatic sea-shore from Adria to Aquileia. After becoming a Roman *municipium* in 49–42 BC, Altinum reached maximum prosperity during the Augustan Age, when new city districts were built

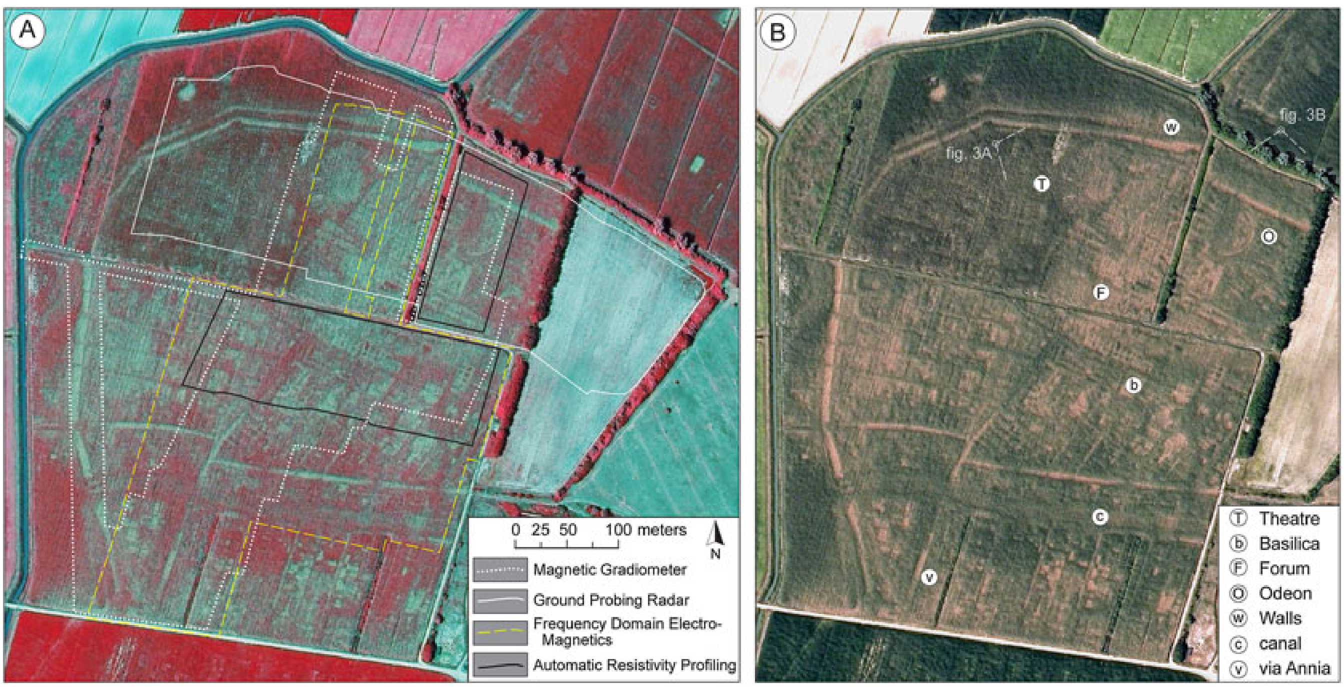

Figure 2. Comparison between two images of the centre of Altinum obtained by colour-composition of spectral bands of the digital aerial picture Realvista 2007 - Telespazio S.p.A. (A) Combination of bands NIR + red + green, with location of the areas surveyed with the geophysical prospections. (B) Combination of bands red + green + blue (pseudo colours), with location of the main archaeological features and the field of view of the oblique aerial pictures of Figure 3A and 3B. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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east of the pre-Roman centre towards the lagoon (Ninfo *et al.*, 2009, Figure 2 in Supporting Online Materials; Tirelli, 2011b). The city was characterized by the presence of theatres, an amphitheatre and forum, large residential areas, a harbour, and was crossed by a large east–west (E–W) oriented canal (Ninfo *et al.*, 2009; Mozzi *et al.*, 2011a, 2011b). A new road connecting Altinum with the town of Tarvisium (Treviso) and the Alpine area, called *via Claudia Augusta*, was constructed in AD 47 (Rosada, 2002).

The decline of Altinum started in the third century AD and continued during the Late Antiquity (Danckers, 2011). In the fourth century Altinum was still an urban centre of importance that was recurrently visited by Roman emperors and also the location of a Bishop's seat at the beginning of the fifth century AD (Calaon, 2006). In a twelfth–thirteenth century faithful reproduction of a fourth century map of the road network in the Roman Empire, the *Tabula Peutingeriana*, Altinum is reported as an important city along the via Annia. Altinum was sacked by the Huns in AD 452 and during the following decades it turned into a military stronghold involved in the Goth–Byzantine war. Altinum was taken by the Lombards in 568, but the Bishop's seat was retained until 639, when it was relocated in the cathedral of Torcello Island.

The remains of multiple superimposed structures from this millennium-long history is an anthropogenic mound that extends for about 1 km^2 and reaches a maximum thickness of about 3.5 m above the underlying alluvial deposits (Ninfo *et al.*, 2009; Mozzi *et al.*, 2011a). Archaeological excavations have been carried out rather systematically in the pre-Roman and Roman necropolis around the town since the 1950s, and in limited sectors at the margin of the Roman city (Tirelli, 2011c), but not in the core of the urban area. In this core area 3–1.5 m below the present surface, test excavations show the presence of earth floors, hearths and remnants of clay-and-wood walls, which are the remains of dwellings and associated work areas from the fourth to the end of the second century BC (Groppo and Pujatti, 2009; Gambacurta, 2011a). Above those relatively simple structures are the foundations of a first century BC to a first century AD wealthy Roman house (*domus*), decorated with rich mosaics, which was destroyed and robbed of building material in the fourth–fifth century AD. Two inhumation tombs without grave goods were then cut into the rubble levels, perhaps in Late Antiquity or early Medieval times. Nearby there are the wall foundations and pools of a bath built at the end of the first century BC to the beginning of the first century AD, which faced a 4.5-m large road constructed of trachyte cobbles (Cipriano, 2010). These thermal bath structures were also partly destroyed in the fourth–fifth century AD.

Geomorphology

Altinum lies at the margin of the Venice Lagoon, on a portion of alluvial plain at the distal fringe of a large distributary fluvial system (megafan) formed by the Brenta River during the Last Glacial Maximum (LGM) (Mozzi, 2005; Fontana *et al.*, 2010, 2014). Alluvial sediments below archaeological deposits are silt and clay with occasional intercalated peat beds and sandy lenses. A well-developed soil with characteristic calcic horizons, locally known as 'caranto' (Mozzi *et al.*, 2003; Donnici *et al.*, 2011), is commonly present around Altinum, and was observed in cores in the city centre at the top of the LGM sediments below the archaeological mound (Mozzi *et al.*, 2011a).

The Holocene fluvial network around the city is represented by the Sile, Zero, and Dese rivers (Figure 1A), which are fed by springs originating in the alluvial plain about 40 km from the coastline. The relative sea level rise after the first century BC is estimated 1.7 ± 0.5 m in this sector of the lagoon (Antonioli *et al.*, 2009). So, in response to relative sea level rise, these rivers have been building small deltas in the lagoon during post-Roman times (Tosi *et al.*, 2007; Primon and Mozzi, 2014). In the Middle Ages brackish swamps surrounded the urban area of Altinum.

Since the Renaissance, significant reclamation works were carried out as the Sile River was diverted from the lagoon in 1684 through an artificial canal ('Taglio del Sile'). A dike was built to defend land from the transgression of lagoon water, due to continuous land subsidence averaging 0.6 mm/yr (Antonioli *et al.*, 2009). During the first half of the twentieth century the area, which is now largely below mean sea level (Figure 1B), was reclaimed and the hydrography is now controlled by draining pumps, which keep the underground water table at average depth of 2 m.

Methods

Remote sensing

A large set of images acquired from aerial and satellite platforms at different times, with visible and multispectral sensors, was used in the research (Table 1). Processing of panchromatic images was conducted through stretching and filtering (directional, low and high pass, Laplacian, Erode, Dilate) (Haralick *et al.*,

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Table 1. Remote sensing images used in the research.

Images	Ground resolution (m)	Spectral bands (nm)	Date	Source
Quickbird	0.61 panchromatic 2.14 multispectral	445–900, 450–520, 520–600, 630–690, 760–900	3 July 2003, 4 September 2004	DigitalGlobe
Realvista Telespazio 2007	0.5	380–600, 480–680, 580–720, 680–1000	31 July 2007	e-Geos S.p.A.
Orthophotos	0.5	Panchromatic	2003, 2006	Regione del Veneto, Compagnia Generale Ripreseaeree S.p.A.
Oblique aerial photographs	0.05	Panchromatic	2007, 2008	Department of Geosciences University of Padua – Via Annia Project

1987). The multispectral images were composed and processed with stretching and band ratio (Figure 2) (Jensen, 1986). The Normalized Difference Vegetation Index and the Vegetation Suppression Index (Crippen and Blom, 2001) were calculated in the multispectral images acquired in the crop season (mainly between May and September). Low altitude (ca. 300 m), oblique aerial images with ground resolution of 3 to 5 cm were also specifically acquired in the growing season, as we knew from previous investigations (Ninfo *et al.*, 2009) that cropmarks are very efficient in the detection of buried archaeological features in the site (Figure 3). High-resolution oblique aerial images were rectified with software AirPhoto (Bonn Archaeological Software Package, BASP) and georeferenced with an accuracy of 10 to 20 cm.

Remote sensing was aimed at detecting the archaeological features in the city centre of Altinum, in order to realize a geometrically-correct map with spatial error < 0.5 m to be used for planning the geophysical prospection.

Geophysical prospections

Prospecting focused on the major public buildings detected with remote sensing, the via Annia, the canal, and the city walls (Figure 2A). They covered an area of approximately 14 ha in the core of the city, which has never been tested by extensive archaeological excavations. The areas of interest for geophysical applications were partly overlapping to allow data comparison and cross-validation. Four geophysical techniques, based on different principles, were used: magnetics, automatic resistivity profiling, multichannel GPR, and FDEM (Table 2).

Figure 3. Aerial oblique pictures taken during flight of 8 September 2009; for location see Figure 2B. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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Table 2. Instruments, field conditions and times of acquisition of geophysical data.

Method	Instrument	Area (ha)	Surface field condition	Last rainfall before survey	Topsoil moisture	Time of acquisition
Magnetic gradiometer	Foerster fluxgate	10	Smooth in S sector; N–S furrows, depth 10–20 cm, spacing 50 cm in N sector	30 mm, 6 days before	Slightly moist	early May 2009, 6 days
Electrical resistivity	ARP©	4	Smooth	15 mm, 5 days before	Slightly moist	early April 2009, 1 day
Ground-penetrating radar (GPR)	Stream-IDS	10	Rough	<1 mm in the last 15 days	dry	early October 2009, 5 days
Frequency domain electromagnetics (FDEM)	Gssi EMP-400	11	Smooth	<1 mm in the last 15 days	dry	early October 2009, 5 days

The magnetometry and FDEM surveys (10 and 11 ha, respectively) were carried out in southwest–northeast (SW–NE) transects, which comprised the via Annia and the bridge on the large W–E canal, the forum, theatre, odeon (small theatre) and limited sectors of the hypothesized city walls (Figure 2A). ARP (4 ha) was concentrated on the forum and the odeon, while GPR (10 ha) covered the northern sector of the city, including the city walls and theatres.

All the tested systems were equipped with a geodetic global positioning system (GPS), operating in real time kinematic (RTK) mode, which provided precise navigation and positioning data. General field conditions, characteristics and times of geophysical survey are synthesized in Table 2.

Magnetometry survey

In this research, a two-wheeled Foerster fluxgate gradiometer was equipped with four probes mounted with equal spacing on a 1.5 m bar. This device is sensitive to microvariations of the magnetic field, performing high-resolution measurements (Becker, 2009). Data acquisition took place along profiles with sampling density of 5 to 10 cm. The cart with the instrument was moved manually. Profiles were spaced 0.5 m apart resulting in a very dense grid. Data acquisition took six consecutive days in early May 2009, when the southern fields had already been sown for maize and the ground surface was rather smooth. The fields north of the major E–W road were ready for soy-bean sowing and had been ploughed, which made them rougher with regular north–south (N–S) furrows (maximum depth 10–20 cm; spacing ca. 50 cm) that introduced a slight background noise in the magnetic measurements. Data acquired along the grids were processed using GIS software Gsys (Powlesland and May, 2010), and interpolated emphasizing values in the range ±15 nT (Figure 4).

Automatic resistivity profiling

Electrical resistivity data were collected with automatic resistivity profiling ARP© system, developed by French CNRS and Geocarta (Dabas, 2009). Electrodes for injecting the current into the ground and measuring the potential are mounted on cogwheels (Figure 5D). The sensors are connected to a high-speed georesistivimeter and have memory for data storage. The device was pulled by an all-terrain vehicle (ATV).

Data acquisition was undertaken at the beginning of April 2009 and was completed in a single day. The ground surface was smooth as the fields were ready for sowing. About 150,000 measures were collected within each hectare (with an average density of 15 samples per square metre), with an inline resolution of 10 cm and 50 cm crossline. Apparent resistivity was mapped on three different pseudo-depth layers from the surface: 0–50 cm, 0–100 cm and 0–200 cm (Figure 5).

Multichannel ground-penetrating radar (GPR)

The survey was conducted using a multichannel cart prototype (Francese *et al.*, 2009) developed by Ingegneria dei Sistemi (IDS SpA) and equipped with 200 MHz antennas. The prototype consists of four modules, each one comprised of eight dipoles with a crossline spacing of 0.12 m. The dipole was oriented in the towing direction.

The GPR survey targeted the northern portion of the city (Figure 6B) and was carried out in five consecutive days in early October 2009. The field conditions were not as good because of the presence of soil clods and crop debris. This caused poor antenna coupling

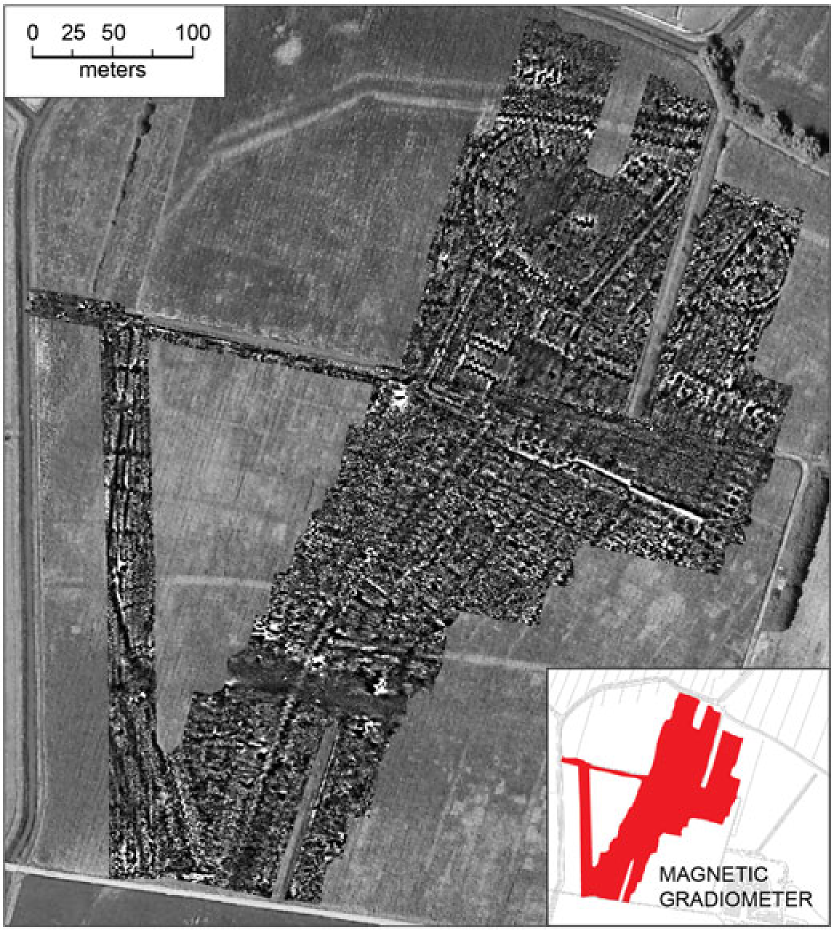

Figure 4. Map of the magnetic gradiometer survey. Image in the background is a grey-tone version of Figure 2B. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

affecting data quality. The four modules were laid out in two rows (shifted laterally 50% of the crossline spacing) and towed by an off-road vehicle at the constant speed of 5 km/h. Using this configuration, 30 transmitting/receiving antennas, in bistatic mode, transmitted radar pulses sequentially. Each antenna was activated every 8 cm resulting in a 6 cm × 8 cm scanning grid along each swath with a coverage of about 210 radar sweeps per m^2.

The time series were processed using *ad hoc* modules (Francese *et al.*, 2009) coded in the open-source environment of the CWP-SU (Colorado School of Mines/Centre for Wave Phenomena – Seismic Unix) package (Stockwell and Cohen, 2008). Particular effort was devoted to the removal of the horizontal banding (Francese *et al.*, 2004) using a moving-average filter.

Frequency domain electromagnetics (FDEM)

The FDEM survey allows for the measurement of the average terrain conductivity within defined depth intervals depending on the primary field frequency and on the coil spacing. The GSSI EMP-400, used in this study, is a multi-frequency device capable of simultaneously measuring three frequencies in the range 1–16 kHz (Won, 1980). Data from a quick test conducted in a small area (10 m × 40 m) showed how the 7 kHz (apparent conductivity of the uppermost few metres) and the 14 kHz (apparent conductivity of the very near-surface layer) provided noise-free results. Based on these results, the total area was surveyed at frequencies of 7 kHz and 14 kHz in early October 2009. The instruments were moved manually. The area was divided in two sub-areas. Sub-area north was covered by 75 lines, each 200 m long and with 1.5 m spacing; sub-area south was covered by 140 lines with length between 135 and 140 m and average spacing of 2.2 m (Figure 6C). In consideration of the average speed of the operator, the distance between consecutive measurements was about 60 cm resulting in a coverage of about one sample every square metre.

FDEM data were processed in the MATLAB environment. A specific filter was designed to attenuate the 'dragging effect', which is typical of data collected

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Figure 5. Map of the apparent resistivity obtained through automatic resistivity profiling (ARP©) considering different pseudo-depth intervals: (A) 0–200 cm; (B) 0–100 cm; (C) 0–50 cm. (D) Picture of the device (Dabas, 2009). Image in the background is a grey-tone version of Figure 2B. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

along parallel lines moving back and forth. The response from the 14 kHz frequency resulted more stable than the one from the 7 kHz, being less disturbed by local fluctuations of the electromagnetic field, and provided the outcome shown in Figure 6C.

Results

Remote sensing provided detailed information on the urban structure of Altinum. Multispectral ortophoto Realvista Telespazio 2007 shows optimal archaeological visibility on most of the study area, clearly showing the location and plan of several archaeological features, such as the forum, basilica, large theatre, small theatre (odeon), the E–W canal, via Annia and street network, city walls, dwellings (Figure 2B). This image, which allowed Ninfo *et al.* (2009) to draw the first archaeological map of Altinum, was integrated by the interpretation of several other images (Table 1). Most remarkable information was provided by cropmarks in oblique photographs, that permitted a very accurate mapping (3–5 cm pixel) of the foundations of the outer and radial walls of the theatre (Figure 3A), of the odeon's outer walls and of a nearby square (Figure 3B). They also showed evidence of a slightly sinuous feature east of the forum, with dimension and cropmarks response similar to the city walls.

The magnetic contrast between soil and archaeological structures led to the collection of excellent and well-readable gradiometric data. The vertical gradient map of Figure 4 shows with lighter grey tones the subsoil with higher magnetic remnant magnetism.

The forum is very well delineated (Figure 6D) and a complex rectangular feature is visible at the western end of the inner square, centred on the forum's short

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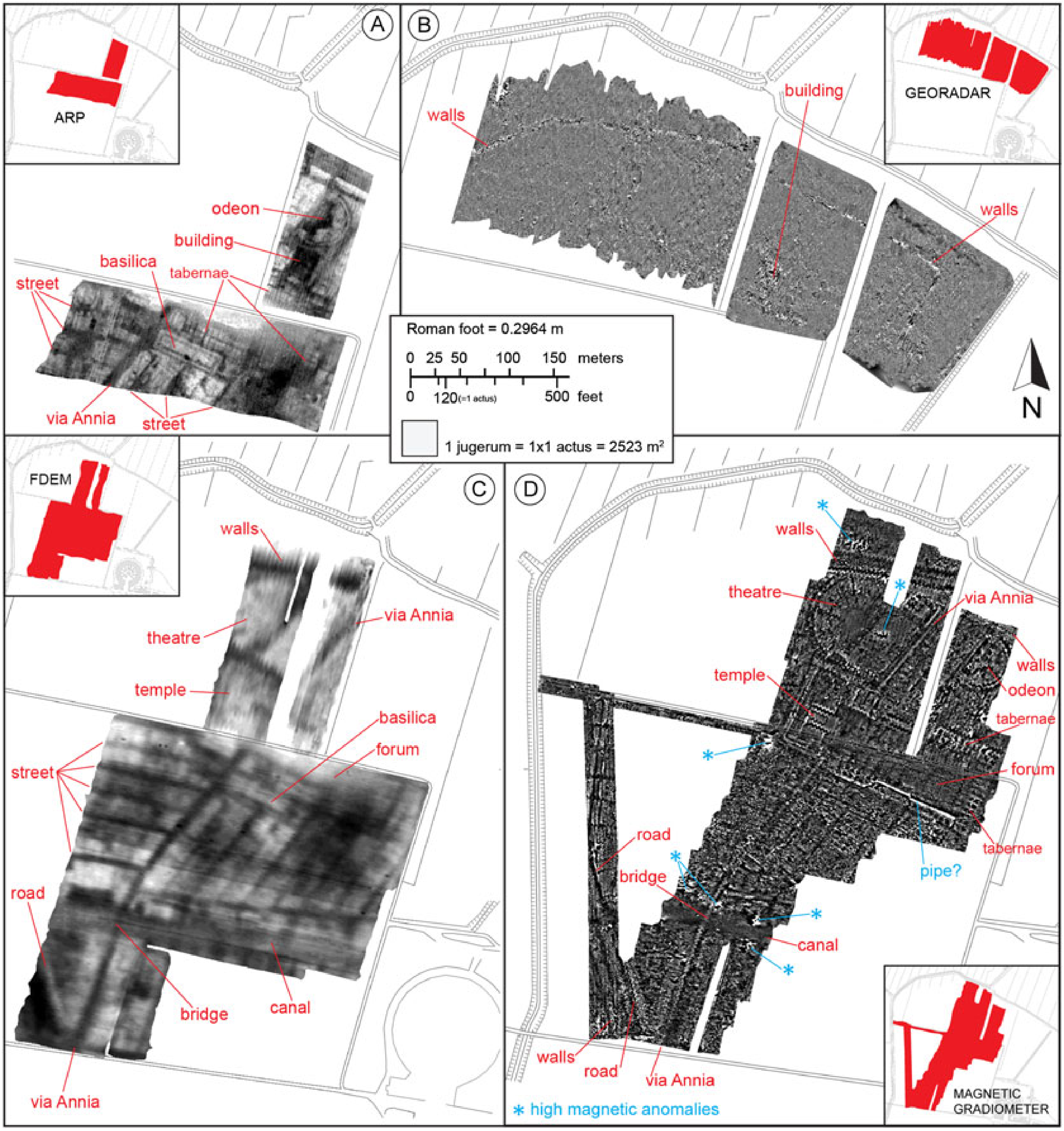

Figure 6. Comparison of the different geophysical techniques used in this research with evidence of the main archaeological features. (A) Map of apparent resistivity surveyed with automatic resistivity profiling (ARP©) considering the pseudo-depth interval of 0–200 cm; (B) map of ground penetrating radar (GPR) survey 20 ns; (C) map of the frequency domain electromagnetic (FDEM) 14 kHz apparent electrical resistivity; (D) map of magnetometry survey, values between +15 nT and −15 nT. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

axis. This structure consists of a building (the smaller rectangle), probably perched on a platform (larger rectangle) and possibly surrounded on three sides by colonnades. These architectural elements match the typical style of Roman temples, as described by Vitruvius and found in many cities (Gros, 1996). Due to its geometry and position, it is probably a temple dedicated to the triad of Roman gods Jupiter, Juno and Minerva, the so-called *capitolium*, which is a common element in the Roman forum. The temple faced the forum's square exactly on the continuation of via Annia. Two symmetric features lie on the sides of the temple, altogether occupying the whole western side of the forum. They probably were buildings or open spaces adjoining the *capitolium*. The possibility that Altinum had a *capitolium* was postulated (Tirelli, 2011d), but previous investigations and remote sensing images did not provide any evidence of its existence.

On the other three sides of the forum square there is a ca. 6 m-wide band suggesting the existence of a colonnade, a typical architectural element of Roman forums. A large number of rooms with an extent of 4 m × 4 m face the portico and they are interpreted as market shops (*tabernae*). Each room is paired by a twin one, open towards the exterior of the forum. Remarkable is the presence of a highly-magnetic linear feature aligned with the shops' walls on the southern side of the forum, probably a metal pipe (*fistula*) used to bring/drain water to/from the forum area. The magnetometry map (Figure 4) shows that some linear features are oriented NNE–SSW that cross the forum, on the continuation of the streets which extend north and south. This suggests that the street network may have existed before the forum was built.

The via Annia shows up very clearly as a highly-magnetic linear feature. Its track is evident also across the E–W oriented canal, suggesting the presence of remnants of the bridge. Two major urban roads, one originating westwards from the via Annia in the southern sector of the city, and another eastwards on the northern bank of the E–W canal, are evidenced by similar magnetic response. A network of minor streets also shows up, even if more blurred. Trachyte rock from the Euganean Hills, near Padua, was extensively used in Roman times for paving roads in the whole northern Adriatic region, and the excavation of small portions of urban roads attests its use also in Altinum (Cipriano, 2010; Tirelli, 2011b). This lithology contains magnetite and ilmenite as magnetic mineral constituents (Capedri *et al.*, 2000; Maritan *et al.*, 2013). The high remnant magnetism along via Annia and other roads in Altinum is probably due to the presence of trachyte slabs in the underground as part of the road pavement. The northern exit of the via Annia from the forum appears as if cut by the walls of the buildings facing the square. This suggests the via Annia entered the forum under arches built between these buildings.

The outer circular walls of the theatre are evident, as well as the traces of some of the radial and concentric walls which supported the seating (*cavea*). This latter appears subdivided in three concentric rings overwhelming the hemispheric orchestra and facing the stage (*proscaenium* and *pulpitum*). The geometry of the theatre follows the usual Vitruvian proportions (Gros, 1996) with the position of the stage front corresponding to the side of the equilateral triangle of 30 m inscribed within the orchestra circle. The theatre may have been 30–40 m high and stood on the highest part of the city, about 4 m above the surrounding plain. Between the theatre and the via Annia there is a large rectangular space. It resembles in shape and position to the area located in front of the theatre next to the 'triangular forum' in Pompei, the so-called *Samnite palaestra* (Pesando, 2000), which was used for athletic competitions of young people and political and military meetings. A similar use can be hypothesized for the area in Altinum, where a very high magnetic anomaly may correspond to pipes or other structures, possibly related to pools/fountains.

The circular walls enclosing the *cavea* of the smaller theatre (odeon) are only approximately delineated by the magnetometry survey. A much better image is provided by ARP (Figures 5 and 6A), which clearly shows the semicircular orchestra and the position of the stage. The odeon appears to be contoured at the back by a narrow street, while the front opens to a larger street parallel to the via Annia. ARP data further show that between the odeon and the forum there is a wide rectangular space. Owing to its dimension and proximity to the forum, this may have been a public space used for large assemblies (*curia*). At the centre of the southern side there is a polygonal feature (dimensions 12 m × 5 m), possibly the foundation of a platform for speakers (*rostrum*) or a major monument. The basilica south of the forum consists of two concentric rectangular structures, probably related to the presence of colonnades within the hall. A southern entrance of the basilica can be seen in correspondence of a street which is parallel to the via Annia, and precisely aligned with the one that faces the odeon.

GPR did not provide relevant data on most of the urban area other than important linear reflectors that run at the northern boundary of the city, showing up at a depth of about 0.7–0.8 m (time slice 20 ns) just below the plough horizon (Figure 6B). These linear features were also detected in aerial images (Figures 2 and 3B) and, on short sectors, in magnetometry, ARP and FDEM surveys (Figures 6 and 7), and are interpreted as the foundations of the city walls. The poor data quality in the GPR map is probably partly related to the

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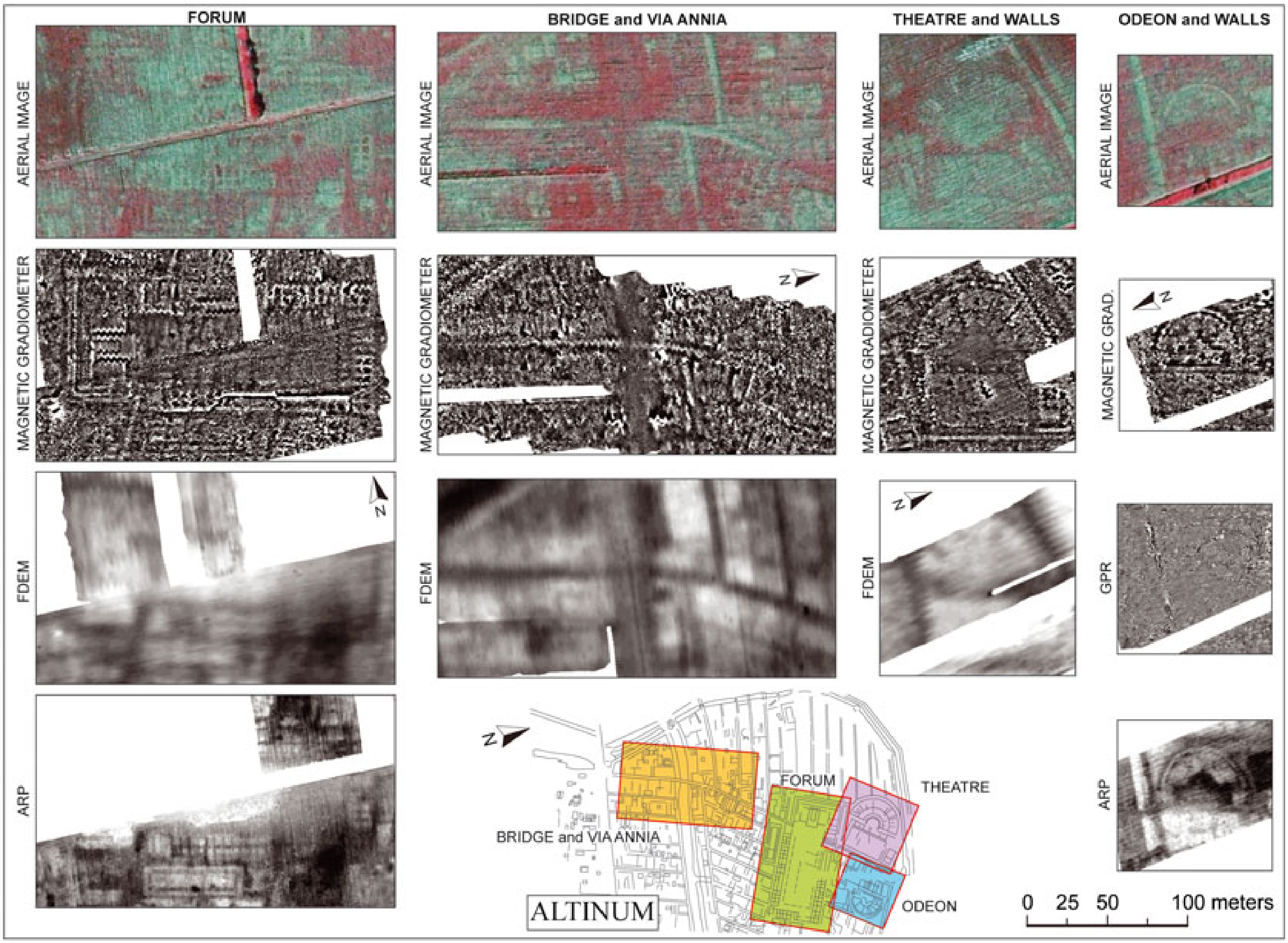

Figure 7. Comparison of the visibility of selected archaeological features in the centre of Altinum with different methods. Aerial image is a combination of bands NIR + red + green of multispectral Realvista 2007 - Telespazio S.p.A. Automatic resistivity profiling (ARP©) images are representative of the pseudo-depth interval 0–200 cm. The frequency domain electromagnetic (FDEM) was acquired with 14 kHz frequency. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

slightly hummocky topography of the fields during data acquisition, which caused bouncing of the instrument and therefore poor energy coupling with the ground.

The FDEM map evidences the general outlook of the street network (Figure 6C). East of the via Annia, streets are parallel to this main road (azimuth 41°) and connect the forum to the road that runs along the canal. West of the via Annia, streets are approximately aligned with the direction of the canal (azimuth 75°). The width of the streets varies from 3.5 m to 5.5 m, while the via Annia and the road along the canal are 4 m wide. To the west of the bridge there is a rectangular area, 45 m × 18 m wide, apparently open to the E–W canal, which may be a boatyard or a space for the unloading and storage of goods (Figure 6C). FDEM shows a subcircular area with an 8 m diameter just east of the bridge (Figure 6C), which corresponds to a marked spike in the remnant magnetism (Figure 6D). Other two similar spikes were detected by the gradiometric survey 40 m further east, on both banks of the canal (Figure 6D). There is evidence of concentrations of ferromagnetic material, possibly related to kilns, smelting or iron working.

Discussion

Archaeological visibility

Cross-validation of different methods indicates that cropmarks remote sensing has a very good capability of detecting buried archaeological structures, and that this information is consistent with geophysical measurements (Figures 2–6). Comparison of main archaeological features from remote sensing and selected

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geophysical methods are found in Figure 7. The low visibility in remote sensing images of the western portion of the forum may be due either to slight differences in field conditions at image acquisition, as cropmarks are very sensitive to local changes in land use and soil moisture, or to the presence of a thicker cover of debris, which hides the underlying structures.

The lack of information in the fields east of the forum and odeon in Figure 2A is evidently related to land use at the time of image acquisition. Oblique aerial photographs of the same fields with ripe maize, shot two years later, show important linear cropmarks interpreted as a main street and part of the city walls (Figure 3B). These features were detected also by GPR, as shown in Figure 6B. A magnetometry survey carried out slightly east of the studied area, in the field at the eastern margin of Figure 2A (Veronese, 2000), confirms the continuation of the city in that direction (Ninfo *et al.*, 2009).

Our magnetometry survey provided good results and when used in conjunction with ARP produced excellent data with very fast acquisition routine and control on the depth of subsoil acquisition. FDEM was useful for providing a general outlook of main structures and a finer data acquisition grid is probably required to overcome this limitation. GPR produced poor results due to ground conditions.

The development of the urban structure

The map of the city in Figure 8 was drawn using all available data. The geometric characteristics of main archaeological structures are reported in Table 3. An attempt of subdividing the city based on its structure and the attribution of different urban uses, highlights the presence of sector 1 which is largely occupied by the theatres and other large public spaces and has direct access to the forum (Figure 9). Sector 2 hosts the basilica next to the forum, while its southern portion shows a rather dense network of minor streets and buildings. Streets parallel to the via Annia are quite evenly spaced, delimiting blocks (*insulae*) which have average widths ranging between 18 and 25 m and length of about 100 to 120 m.

Sectors 4–7 are also regularly subdivided by streets and contain many small buildings, probably houses and shops/workshops. Indeed, sporadic archaeological findings in these latter sectors indicate the widespread presence of floors (Paveggio, 2011). These

Figure 8. Synthetic map of the centre of the city of Altinum based on remote sensing and geophysical data. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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Table 3. Dimension in metres and Roman feet (1 Roman foot = 0.2964 m), and orientation (azimuth relative to geographic north) of main archaeological structures.

Structure	Length and width of rectangular structures/theatres' radius		Azimuth of long axis/theatre's stage
	m	Roman foot	Degrees
Forum overall	199 × 87	671 × 294	117
Forum interior	156 × 58	526 × 196	117
Forum shops	6 × 6	20 × 20	117
Temple overall	29 × 16	98 × 54	115
Temple interior	17 × 7	57 × 24	115
Curia	36 × 26	121 × 88	24
Basilica overall	69 × 20	233 × 67	117
Basilica interior	55 × 9	186 × 30	117
Palaestra	66 × 35	223 × 118	42
Theatre overall	44	148	42
Theatre orchestra	17	57	42
Theatre tage	71 × 7	240 × 24	42
Odeon overall	24	81	33
Odeon orchestra	8	27	33
Odeon stage	27 × 7	91 × 24	33
Via Annia	4 (width)	14	21–42
Canal	13 (width at bridge)	44	88–99
City walls	4–5 (width)	13–17	8–40–70–98–120–214–346

presumably private buildings are organized in blocks which are up to 120 m long and have widths between 27 and 52 m.

Sector 8 occupies a rather peripheral position at the back of the forum and theatre, without a direct access to via Annia. As in sector 7 here blocks have very regular dimensions, showing an average width of 22 m. Unfortunately at this location the applied methods (remote sensing and GPR) did not provide further evidence on archaeological structures within the *insulae*.

Sector 3 extends along the banks of the canal and shows evidence of structures related to trading and workshops.

The city walls are a clear demarcation of the city boundary. At the outer foot of the walls in the north-west sector there are linear features interpreted as a parallel road.

A combination of all geophysical and remote sensing evidence shows that the political, economic, and religious centre of the city was in the northern part, comprising sector 1, the forum, and the areas of sector 2 next to the forum and via Annia. Main craft and trading activities were probably concentrated in sector 3, while the other sectors appear to have been mostly residential.

The archaeological features recognized through remote sensing and geophysics form a complex palimpsest map, in which chronological differentiation is not straightforward. Nevertheless, the organization of these features suggests the existence of a unitary urban plan with two elements, the via Annia and forum, playing a pivotal role. As the road was most probably built in 153 BC (Rosada *et al.*, 2010), this configuration of the city at this time should be contemporaneous or post-date it. The orientation of the *domus* built in the second half of the first century BC (Groppo *et al.*, 2010) is the same as the forum (azimuth 117°), suggesting that it was contemporaneous or successive to it. The only available chronological indication for the public buildings comes from a fragment of the cornice of the theatre, found in the 1950s and attributed to 40–20 BC (Sperti, 2011). Based on these indications, it seems probable that the city assumed the outline reconstructed in Figures 8 and 9 between the second half of second century and the end of first century BC.

While Altinum is not a city with a Roman foundation as it had a long history as a major Iron Age settlement, there seems to be little trace of the earlier urban network. The anomalous bend at the western end of the canal, between the Annia bridge and the exit across the city wall, suggests that this waterway may have been a pre-existing element as a canal excavated after or contemporaneously to the via Annia would have probably been straight. Furthermore, the street at the boundary between sectors 3 and 7 also bends parallel to the canal, as if it was forced to follow its banks.

Another point to be considered is that the city walls presumably did not play any defensive role in the first part of the Imperial Age, as Altinum was in a peaceful setting inside the Roman Empire (Tirelli, 2011b). The theatre almost completely occupies the space between the forum and the city walls, as if it was purposely built in a vacant lot between them. This suggests that the city walls pre-date the construction of the theatre. It is possible that the city walls date back to the times of Romanization and that they follow a layout related to the Iron Age city. In the Imperial Age these earlier components may have been partly dismantled, refunctionalized as roads or kept as symbolic urban landmarks. Indeed, the only excavated portion of the city walls, a first century BC door facing a canal at the eastern end of Altinum (Tirelli, 2004), outside of our study area, has been interpreted as a monumental architecture rather than an effective defence. During the political instability and wars of the Late Antiquity, when Altinum was still an important urban centre (Calaon, 2006; Christie, 2006), there may have been a

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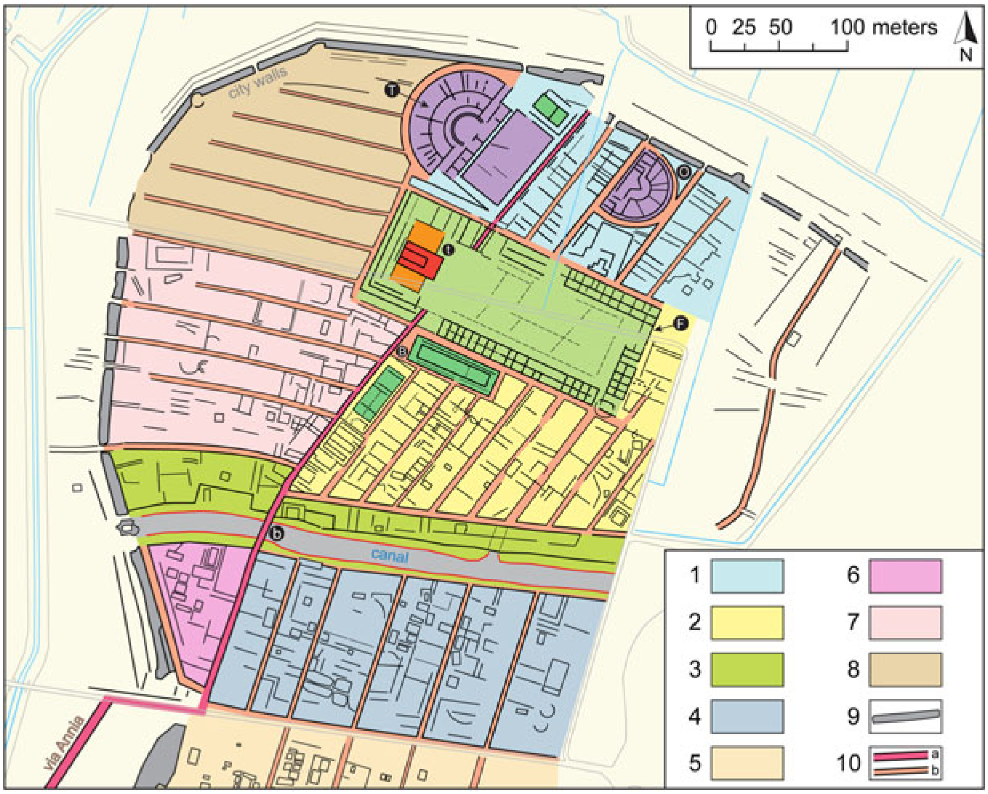

Figure 9. Interpretative map of the centre of the Roman city of Altinum with evidence of the main public buildings, the street network and the city walls. Colour fills represent a tentative division in urban districts. F, forum; t, *capitolium*; T, theatre; O, odeon; b, canal bridge. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

restoration of previous walls, which were again set up to effectively defend the city. This would be consistent with some rearrangements observed in the excavated sector (Tirelli, 2004). The excellent evidence of the city walls from remote sensing and geophysics suggests their good preservation, which can be partly related to this later rebuilding. A controversial point is the regular interruption of the city walls north of the canal, in correspondence of some major E–W streets. These breaks may correspond to drainage outlets in the walls that allowed channelling away runoff and sewage. The outlets may have been enlarged after the abandonment of the city in order to cut passages through the walls and remove building materials from the city centre.

Conclusions

Our research produced unprecedented information on the subsurface archaeology of Altinum, leading to the detailed definition of the urban plan and the new discovery of key sites, such as the temple at the western end of the forum. Even though the city was largely destroyed and robbed of stone during the Middle Ages, many archaeological structures detected through remote sensing appear to be partly preserved below the plough horizon at least down to a depth of 2 m. This investigation demonstrates that large portions of floors and foundations of public and private buildings are still present in the immediate subsoil of the urban centre where mosaics and rock-paved floors could be preserved.

The precise mapping of such a complex, buried urban setting was carried out in a few days of fieldwork thanks to the powerful integration of different high-resolution imaging techniques. Georeferencing of the geophysical data, and their fusion and comparison with traces in the ortho-rectified aerial images, allowed to precisely locate the archaeological structures with an estimated error < 0.5 m over an area of about 14 ha. The extent and detail of the produced map (Figure 7) would be not reachable with 'classical' surface and stratigraphic archaeological surveys, which would also need a far stronger effort in terms of time and money.

Further stratigraphic tests are needed to check specific zones and to allow the collection of chronological information supporting the results of our indirect investigations. But future soundings (e.g. corings, trial trenches, and excavations) can now be planned with high accuracy and an efficient cost-effect strategy, limiting their number and extent to specific targets.

Every technique applied in the site produced an image that is itself a map of part of the city, providing images of particular buried features. The multispectral aerial photo Realvista 2007 provided a complete view of the city and extraordinary cropmarks of the buried archaeological features. Other vertical aerial photographs gave far less information, while some of the oblique pictures taken along the crop season were very powerful in providing detailed data and particulars, which were not detected in the photo Realvista 2007. Nevertheless, cropmarks do not always allow the discrimination of features that relate to spoliation trenches from those relative to structures that are still *in situ* (e.g. walls, floors, streets). Thus, comparison with geophysical methods is necessary for assessing the preservation of buried structures.

Among the geophysical techniques, magnetic gradiometer and ARP turned out to be the most efficient in Altinum. Magnetometry survey supplied a very detailed and precise map, giving new important clues about the internal structures of large buildings and about the underground setting of the forum square. The temple at the western side of the forum is clearly detected in the magnetic map, while it is not visible with other geophysical or remote sensing methods. ARP produced a very detailed map, especially at the time-slice at depth of 1–2 m, that allowed to detect some inner structures not visible with other methodologies. FDEM was very efficient in mapping the street pattern, but it was only slightly sensitive to other minor elements mostly because of the coarse grid. The GPR clearly traced the perimeter of the city walls, but it failed in detecting most of the other structures, even the theatre that is so visible with all the other methods. Better GPR images may be possible if collected with a smoother ground surface. However, the results suggest that future geophysical surveys, eventually with a more detailed sampling on some large building and public areas, should mainly focus on magnetic and ARP methods.

The archaeological reconstruction shows that Roman Altinum was the product of a unitary urban plan, having the via Annia and the forum as main axis, and incorporating few elements of the previous Iron Age settlement. This urban structure, which illustrates the presence of different districts with specific characteristics and use, derives from a re-organization of the city which probably occurred between the second half of second century and the end of the first century BC. It is unclear which modifications occurred during the Late Antiquity.

Roman Altinum is evidently shaped by a centripetal urban project, which adheres to standardized models found across the whole Roman Empire. Nevertheless, trading and productive activities at Altinum appear to have been concentrated along the canal which crossed the city centre and connected it to the lagoon. The city itself represented a landmark of vital importance along this low, monotonous and misty coast, as its main buildings, such as the theatre, were at least 40 m high and could be seen from a distance of 20 km. While conveying a message of political and economic power, the city skyline may thus have also functioned as a useful nautical way-point for the ships entering the lagoon from the northern Adriatic, and heading to the harbour located on the lagoon shore at the outskirts of the city (De Bon, 1938; Ninfo *et al.*, 2009).

All this indicates the double-fold character of Altinum. On the one hand, it was a standard Roman city at the crossroads of two major consular roads, projected towards the mainland. On the other hand, it was a harbour city open to the lagoon, where it could control the maritime traffic across a vast labyrinth of salt marshes and tidal channels, as well as the exploitation of strategic resources such as fish, salt, and seafood (Cresci Marrone and Tirelli, 2003; De Min, 2006). As discussed by Ammerman (2012), the urban fabric of Roman Altinum is different from the eighth century early Venice, while Torcello possibly represents a first prototype of a major, fully lagoonal settlement which pre-dates the Venetian sites at Rivoalto. Nevertheless, people from Altinum most probably had full acquaintance with the lagoon, which was a vital part of the economic system of the city and not just a marginal territory.

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