



## High resolution space and ground-based remote sensing and implications for landscape archaeology: the case from Portus, Italy

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### ABSTRACT

Ground-based archaeological survey methods, together with aerial photography and satellite remote sensing data, provide archaeologists with techniques for analysing archaeological sites and landscapes. These techniques allow different properties to be detected dependent on the nature of archaeological deposits, although clear restrictions exist, either with their physical limitations, or in the extent and nuances of their application. With recent developments in landscape archaeology technologies, it is increasingly necessary to adopt an integrated strategy of prospection, incorporating both ground-based non-destructive methods and remotely sensed data, to understand fully the character and development of archaeological landscapes. This paper outlines the results of a pilot project to test this approach on the archaeological landscape of Portus, the port of Imperial Rome. Its results confirm the potential that exists in enhancing the mapping of this major port complex and its hinterland by means of an integration of satellite remote-sensing data, geophysical survey and aerial photography. They have made it possible for new questions to be raised about Portus and its environs and, by implication, suggest that integrated fieldwork strategies of this kind have much more to tell us about major Classical sites and other large and complex sites across the globe than by addressing them by means of single methods alone.

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### 1. Introduction

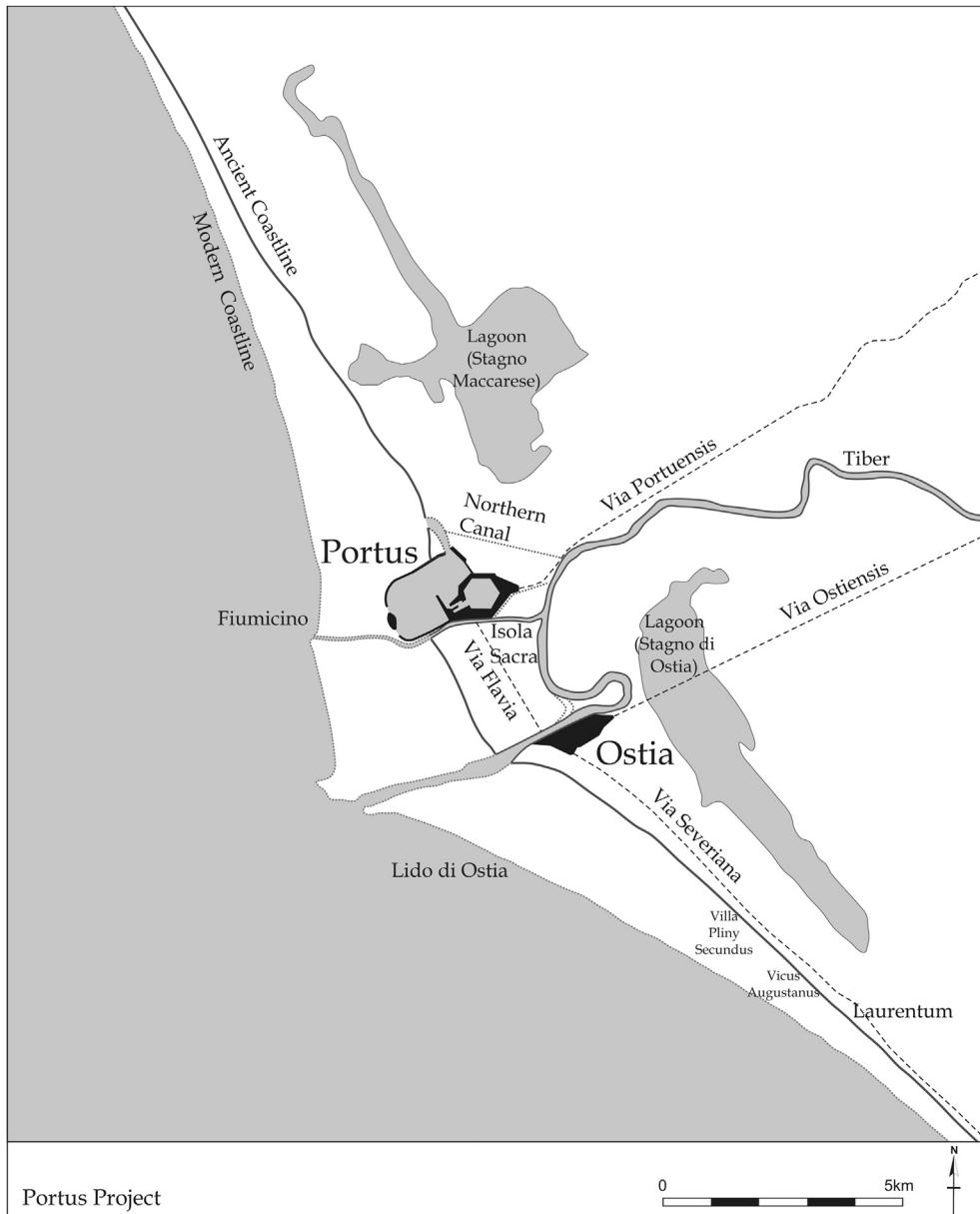
Archaeological survey and aerial photography have played an integral role in the analysis and recording of sites in Classical archaeology. Archaeologists have used field-walking methods to provide broader data on the presence, absence and dating of settlements in the landscape since the 1950s (Potter, 1979). Aerial photography has allowed the mapping of the nature and extent of visible and buried archaeological remains (Guaitoli, 2003; Jones, 1999), stemming from the systematic coverage produced by the RAF, Luftwaffe and USAF in the Mediterranean region during WW2 (Mazzanti, 2006). Targeted geophysical survey has provided a useful companion to non-destructive methodologies on landscape surveys in the Mediterranean (Barker, 1997). Only more recently has technological development facilitated the integration of ground-based and remotely sensed survey methods.

Application of topographic and geophysical survey, with more widespread use of remote sensing technologies, has changed the

perspective and approaches of Classical archaeologists (Pasquinucci and Trément, 1999), and especially the approach to ancient urban mapping, in the last decade (such as Buteux et al., 2000; Neubauer et al., 2002; Alcock and Cherry, 2004; Hay et al., 2006; Vermuelen et al., 2012; Johnson and Millett, 2013). This has had a dramatic impact upon our understanding of the Classical world, even though many interpretational issues remain, relating to the form and nature of anomalies represented in datasets, the dating and phasing of complex data where little or no tangible evidence is available for use in conjunction with survey results, and in comparing results from different surveys (Alcock and Cherry, 2004). The large scale of the work conducted at sites in Europe, including Wroxeter in the UK (Gaffney et al., 2000), Falerii Novi and Portus in Italy (Keay et al., 2000, 2005) has enabled a more detailed understanding of urban centre plans. Integration of these methods has allowed the mapping of archaeological features, including streets, roads, buildings, industrial features, cemeteries, and tombs, across a large area of landscape. The application of remote sensing and geophysical survey has provided a relatively cost-effective and efficient approach to surveying classical sites. The methods allow high resolution data collection, reducing the need to excavate large areas. Limitations do exist with the use of non-destructive methodologies. The nature of

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**Fig. 1.** Location of Portus, showing the main sites mentioned in the text.

buried archaeological materials will affect the ability of different techniques to detect features, and results can be open to over-interpretation, fitting the anomalies present in the datasets into prescribed hypotheses or notions of a particular site or landscape. This paper presents the results of a pilot project<sup>1</sup> that attempts to explore the potential of using additional non-destructive methods on major Classical sites. We integrate high-resolution satellite data with results from previous geophysical surveys, and calibrate the results via further targeted fieldwork.

The landscape of Portus demonstrates the need for a multi-faceted approach to the study of the archaeological site and its surrounding landscape. From the beginning of the geophysical survey at the site in 1998, and the Portus Project in 2007, the team

has applied different methods of ground-based survey to assess the nature of archaeological remains (Keay et al., 2008a, 2008b, 2009, 2011, 2012a, forthcoming; Goiran et al., 2009; Ogden et al., 2010; Strutt and Keay, 2008). With such a background of a complex palimpsest of sub-surface and extant archaeological deposits, the authors of this paper applied multi-scalar, multi-temporal, and multi-spatial survey approaches in order to enhance our understanding of the site and its region, and to explore new ways of framing research questions and hypotheses relating to the site. It is hoped that the results will serve as a model for other major archaeological projects which use survey on complex sites of significant historical importance.

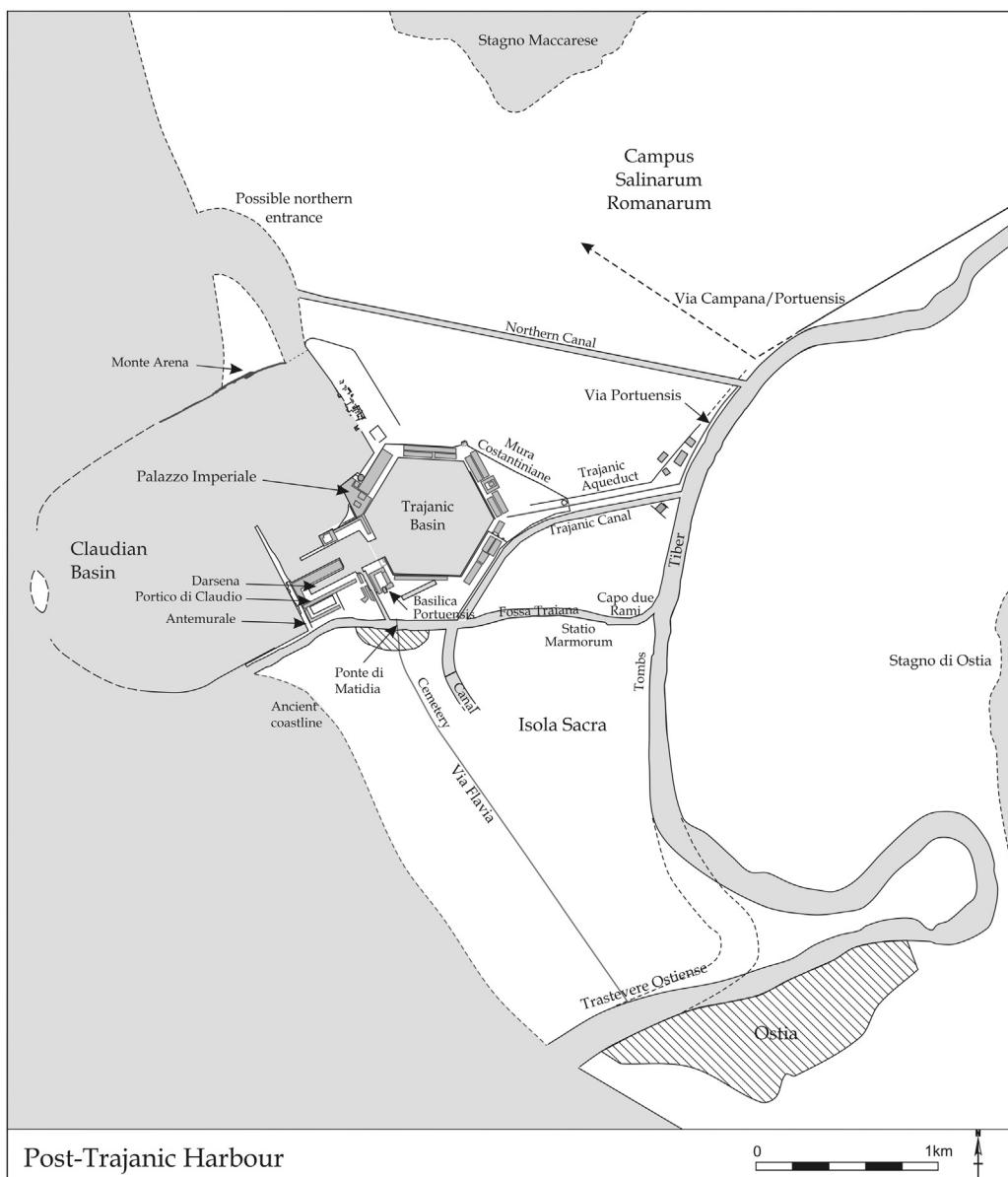
## 2. Archaeological context and discussion

Portus, constructed in the Tiber delta on the ancient Roman coastline is located some 35 km to the south-west of Rome, to the

<sup>1</sup> The work was undertaken at the behest of, and funded by, the BBC/Discovery in collaboration with the Portus Project and the UAB as part of the television programme "The Roman Empire: What Lies Beneath".

north of the river Tiber and less than a kilometre to the south of the Aeroporto di Fiumicino, Rome's principal airport (Keay et al., 2004, 2005, 2009) and 3 km to the north of the river port of Ostia Antica (Fig. 1). The emperor Claudius initially established the port in the mid 1st century AD as an entirely artificial construction, with its central feature comprising a massive harbour basin (200 ha) and lighthouse. Initially intended as an extension to the anchorage available at Ostia, the port also served to help alleviate seasonal flooding of the Tiber in the area to the south of Rome (Keay et al., 2005). Trajan substantially enlarged Portus, with the construction of a new hexagonal basin (32 ha), a short distance inland from the earlier harbour. The site saw further additions under later emperors in the course of the 2nd and 3rd centuries AD (Fig. 2) with a view to converting the port into a conduit for the supply of foodstuffs, marble and a range of other material to Rome from across the Mediterranean. The volume of commerce dropped around the later 5th century AD.

Although the existence of Portus has been known since at least the 16th century, relatively little archaeological research at the port complex or its hinterland has taken place. Early work (both sporadic and episodic) focused on the port (Lanciani, 1868; Lugli and Filibek, 1935) or the landscape and toponyms of the surrounding area (Nibby, 1849). Later rescue work took place in the Claudian basin during the construction of the airport (Testaguzza, 1970), and also includes more recent programmes of focused excavation and restoration by the Soprintendenza Speciale per i Beni Archeologici di Ostia (Mannucci, 1992). Archaeologists have directed less attention towards the hinterland, aside from excavation of the cemetery and associated settlement in the Isola Sacra between Portus and Ostia to the south, and in the area of the *Campus Salinarum Romanarum* to the east of the port. Workers drained much of this former malarial area in the early 20th century as part of the *Bonificazione* of the delta, giving rise to a landscape characterized by sporadic mixed pastoral and cereal farming. Today, however, the



**Fig. 2.** Plan of the site of Portus in the Late Antique period.

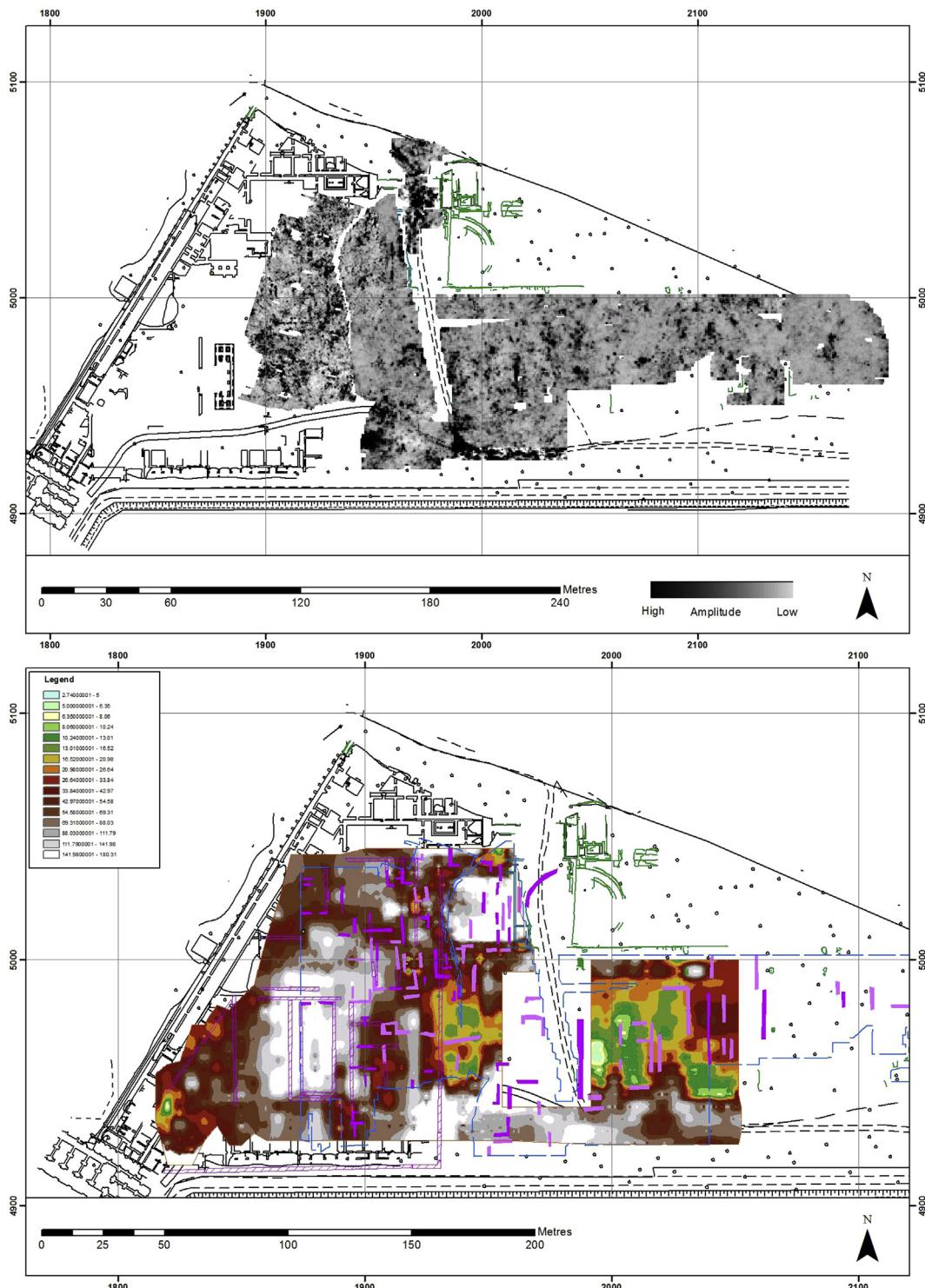


**Fig. 3.** Plan of the magnetometry and resistivity surveys of the *Palazzo Imperiale* area, with a basic plan of the excavations at Portus from 2007 to 11.

site suffers from the intrusion of urbanization and rapidly expanding transport systems.

The current programme of survey and assessment of remotely sensed data has its origins in a large-scale geophysical survey of Portus and part of its hinterland (Keay et al., 2000, 2005) conducted between 1998 and 2005. This consisted of a magnetometer and

topographic survey of c. 220 ha, incorporating the warehouses and public buildings bordering the Claudian and Trajanic basins and areas lying to the east. The Portus Project ([www.portusproject.org](http://www.portusproject.org)) subsequently built upon these results to undertake archaeological excavation at the so-called *Palazzo Imperiale* (Keay et al., 2011) and adjacent buildings (Keay et al., forthcoming) at the centre of the



**Fig. 4.** Images showing the results of the GPR survey in the area of the so-called *Palazzo Imperiale*, with interpreted features superimposed on the modelled ERT data for the area.

port in the context of a programme of more focused geophysical survey (Keay et al., 2008b). This complemented a programme of extensive geophysical survey across the whole of the Isola Sacra (Germoni et al., 2011).<sup>2</sup>

### 3. Materials and methods

#### 3.1. Geophysical survey methods

Since 2007, the Portus Project has conducted magnetometer surveys of Portus using Bartington Instruments Grad601 fluxgate gradiometers, with measurements taken along traverses spaced 0.5 m apart, at 0.25 m intervals, producing results with a very high

<sup>2</sup> Coordinated by Martin Millett (University of Cambridge) in conjunction with Simon Keay, Kristian Strutt and Paola Germoni.

**Table 1**

Survey methods and remotely sensed data used by the project, and the principal archaeological and geomorphological materials that each technique locates.

Method	Field-based or Remote	Instrument Used	What they detect
Fluxgate Gradiometer Magnetometry	Field	Bartington Instruments Grad 601 fluxgate gradiometer	Brick, tufa walls and vaults, basalt road surfaces, volcanic sediments and beach sands, canal sediments, ceramic surface scatters
Earth Resistance	Field	Geoscan Research RM15 resistance meter	Brick, tufa, travertine walls and vaults, canal sediments, rubble areas, shallow road surfaces
Electrical Resistivity Tomography	Field	Allied Associates Tigre 64 probe system	Brick, tufa, travertine walls and vaults, canal sediments, rubble areas, shallow road surfaces, underlying geomorphological deposits
Ground Penetrating Radar	Field	GSSI 400 MHz antenna with SIR-3000	Brick, tufa walls and vaults, basalt road surfaces, paving, concrete sub-structures
LiDAR Air Photography	Remote	Airborne LiDAR equipment	Topographic variation, earthworks, extant remains
	Remote	RAF, USAF and Aereo Militare photos alta quota and bassa quota	Areas of seasonal flooding, canal sediments, excavated structures, shallow buried walls, revetting, dune cordons
Satellite: Panchromatic	Remote	Worldview 2 panchromatic resolution 0.8m	Modern structures, excavated remains, shallow buried structures
Satellite: Multispectral	Remote	Worldview 2 Multispectral resolution 1.2m	Modern structures, excavated remains, shallow buried structures, ancient meanders courses, lagoon areas

resolution. Analysis of the results allowed the team to target areas with Ground Penetrating Radar (GPR) survey. This has allowed the relative depth of archaeological deposits at certain parts of the site to be established, and for the survey of those areas where the modern ground surface or surrounding ferro-magnetic disturbance made magnetometry impossible. Archaeological survey included the use of either Sensors and Software 500 MHz antennae, or GSSI 400 MHz antennae. Survey over the *Palazzo Imperiale* employed traverse spacing of 0.25 m, resulting in results with a very high resolution.

Near the *Palazzo Imperiale* a programme of integrated geophysical survey, that involved Electrical Resistivity Tomography (ERT) and GPR, located an early quay measuring over 70 m in length, while immediately to the south the survey revealed the internal organization of a building (Building 5) c. 240 m long running parallel to the Trajanic Basin (Fig. 3) (Keay et al., 2008b; 2009; forthcoming; Strutt and Keay, 2008). ERT and GPR surveys over the *Palazzo Imperiale* have also aided in the interpretation of structural remains, incorporating evidence from building survey within the open corridors and rooms of the complex, to produce a plan of standing and buried structural remains across this area of the site (Fig. 4). The extensive excavations conducted in these areas have allowed testing of the geophysical survey results. The GPR and ERT have also defined the location of a number of key port structures, including the eastern sector of the *Palazzo Imperiale*, and the relationship between the *Palazzo* and an adjacent amphitheatre-shaped building (Keay et al., 2011). Details of a very large building running along the edge of the Trajanic Basin to the north of the *Palazzo Imperiale* were also defined in the GPR and ERT surveys (Keay et al., forthcoming), with excavation now revealing the presence of a possible shipyard (Fig. 4).

Survey of the hinterland of the port to the south involving magnetometry and topographic survey, has exposed an extensive system of man-made small channels or canals subdividing the Isola Sacra between Portus and Ostia Antica. The line of the Via Flavia linking the river port of Ostia Antica with Portus also appeared, together with a channel measuring 90 m at its greatest width (Germoni et al., 2011; Keay et al., 2012a), and traces of a hitherto unsuspected stretch of the northern town wall of Ostia as well as a series of large warehouses and other buildings measuring some 300 m by 120 m, overlooking the Tiber to the north of Ostia (see Fig. 11 below).

The use of geophysical survey at Portus and in its hinterland has provided the Portus Project with a rapid and high resolution means of mapping the nature and extent of archaeological and

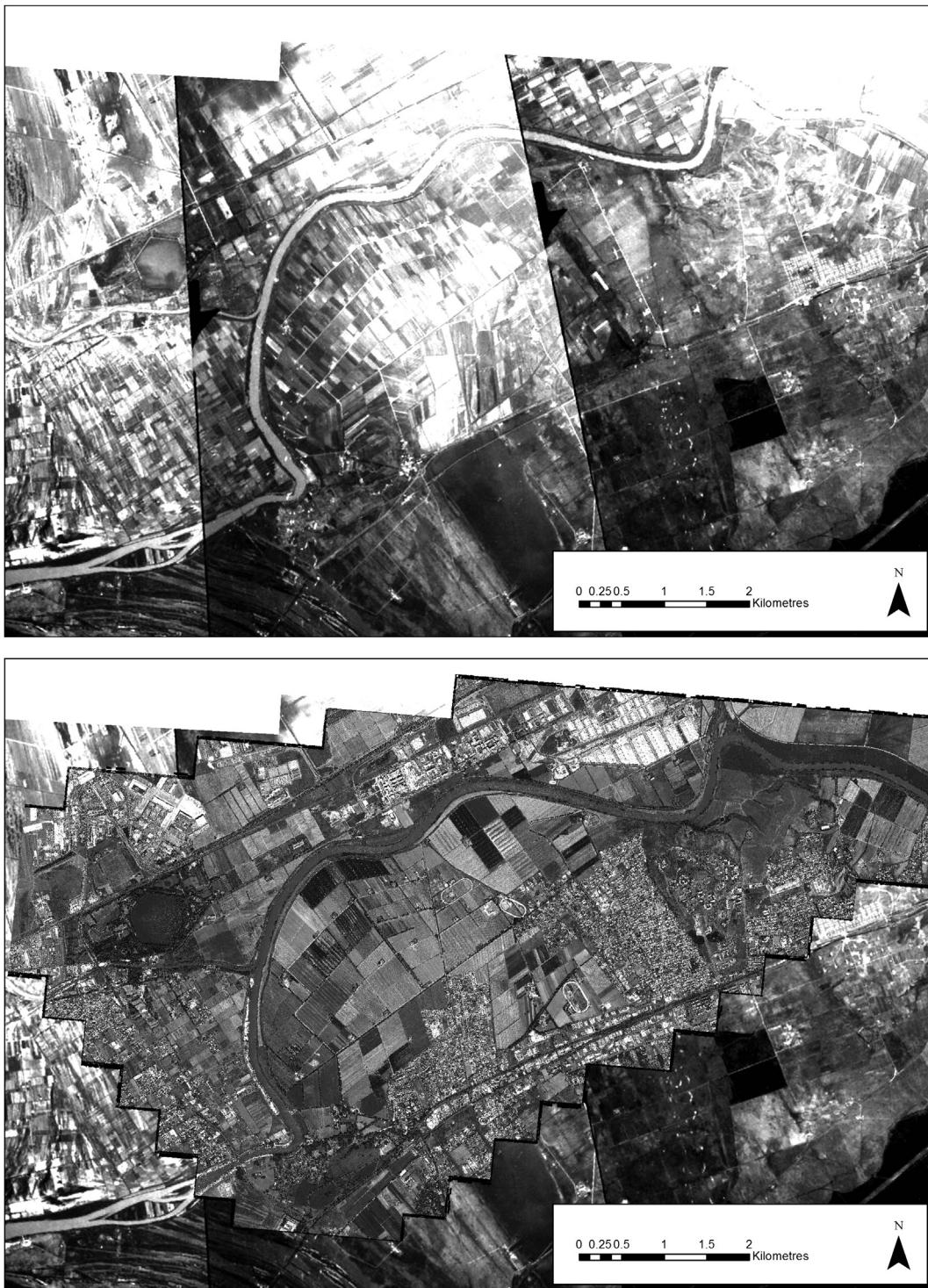
geomorphological features (Keay et al., 2005; Germoni et al., 2011). The materials utilized in the construction of much of the port infrastructure, including fired brick and tile, tufa, and basalt, all with a relatively strong remnant magnetism, have facilitated the mapping of complexes of structures, warehouses, roads, canals and the defensive walls of Portus. More recently, the variation in alluvial sediments across the floodplain, human activity in the creation of port infrastructure, the creation of systems of smaller waterways possibly associated with land division, pastoral land use, and industrial activity such as salt extraction, provide an ideal environment for the use of magnetometry in mapping the environs of Portus between the harbour and the river port of Ostia Antica.

### 3.2. Satellite remote sensing methods

These surveys have provided high resolution data with which to identify archaeological features across the port and its hinterland, across an overall area of c. 450 ha. A number of questions relating to specific areas within the port, and the more general distribution of the settlement and port, however, still needed to be addressed. Magnetometry results did not have equal representation of all feature types due to the nature of their building materials. For instance structural remains not built from brick and tufa material are not always visible in the magnetometer survey results (Table 1). Some areas also proved impossible to access on the ground during the survey. Aerial photography, satellite remote sensing (SRS) and LiDAR data could thus be used for comparative purposes with the geophysics, and to fill in areas not accessible during the survey (Fig. 5). The SRS analysis in particular focused on areas where questions still remain about the results of earlier geophysical surveys, or gaps in our coverage, which included the recently identified site of the Pharos<sup>3</sup> to the west of the port, the floodplain between the port and Tiber to the east, and the line of the Via Flavia that headed southwards to Ostia. While SRS has played a critical role in the identification of archaeological features and sites globally (Wiseman and El-Baz, 2007; Parcak, 2009) little work exists which critically assesses its applications and limitations, and the instances where it may or may not be applicable.

In view of all of the above, and in the context of an initiative undertaken within the context of a BBC/Discovery television

<sup>3</sup> Italian archaeologists of the Soprintendenza Speciale per i Beni Archeologici di Roma have identified the site of the Pharos in this region from the analysis of concrete fragments from deep cores: Morelli et al., 2011).



**Fig. 5.** Comparative aerial photography from 1943 to 44, (top) and overall satellite imagery of Portus and environs (below).

programme exploring the potential of satellite-based analysis, the Portus team in 2012 experimented with the use of geophysical survey techniques as a method of ground truthing for anomalies identified from multispectral satellite imagery analysis, both at Portus itself and in the Isola Sacra. The team targeted locations that included land on the north bank of the Tiber opposite Ostia Antica, two areas along the line of the Via Flavia, the playing field and pasture to the east of the Episcopio between the Fossa Traiana and the Trajanic basin at Portus, and an area on the east bank of the

Tiber to the north of Ostia Antica using the UTM 32N coordinate system.

We obtained 28 km<sup>2</sup> of multispectral Geoeye-1.5 m (from July 18, 2010) and 32 km<sup>2</sup> of WorldView-2 0.5 m satellite data (from September 2, 2011), in addition to 40 km<sup>2</sup> of LIDAR 1 m data from 1988. Geoeye-1 data contains 4 bands (Red, Green, Blue and NIR), from 450 to 900 nm, with 0.41 m panchromatic and 1.65 m multispectral imagery. This is pansharpened by Geoeye for 0.5 m multispectral data (Geoeye, 2012). WorldView-2 satellite imagery

contains 8 bands (Red, Green, Blue, Yellow, Coastal, Red Edge, NIR1, NIR2), from 400 to 1040 nm, with a 0.46 m panchromatic resolution and 1.85 m multispectral resolution (DigitalGlobe, 2009). Both imagery types are resampled to 0.5 m due to NOAA regulations. Historically, archaeologists have obtained aerial photographs of European field landscapes during the hot summer months (June–July), assuming that is the optimal time to view changes in vegetation health and height differences (i.e., crop marks) indicating shallow subsurface archaeological features (Shell, 2002; Trier et al., 2009). Visually, the July Geoeye-1 imagery revealed virtually identical features to the 1943 and 1944 aerial photography. Temperature and weather patterns must be understood when conducting SRS, and an extremely wet or dry month can unexpectedly optimize standard remote sensing applications (Mumford and Parcak, 2002; Parcak, 2007; Saturno et al., 2007). Testing a range of satellite imagery and survey methods on any landscape is essential in maximizing the features that can be visualized, especially with regards to weather and temperature patterns.

We first pansharpened the WorldView-2 image (using ERDAS ER Mapper) to obtain 0.5 m multispectral data. Because subsurface features on Roman period sites in Europe affect the general health or productivity of overlaying vegetation (Lasaponara and Masini, 2007), we applied a Normalized Difference Vegetation Index (NDVI) on bands 4 and 3 in the Geoeye-1 imagery, and bands 8 and 6 in the WorldView-2 imagery. An NDVI formula allows the user to measure the health of vegetation in satellite imagery, which is typically Band 4-Band 3/Band 4 + Band 3 in 4-band or NASA imagery such as Landsat (Lillesand et al., 2008). In WorldView2, Bands 8 and 6 represent the Red-Edge and IR bands. Multiple NDVI tests on the WorldView-2 imagery involving Bands 5 (Red, 630–690 nm), 6 (Red edge 705–745 nm), 7 (NIR1 770–895 nm) and 8 (NIR2 860–1040 nm) showed the greatest vegetation health differences above potential archaeological features when using Bands 8 (not affected as greatly by atmospheric issues) and 6 (useful for detecting plant chlorophyll production). Not only is seasonality important when determining which image types and techniques to apply during satellite data processing, but the specific parts of the light spectrum affected by subsurface archaeological remains must also be carefully considered. We also applied an 11 × 11 high pass filter and Gaussian Equalization for feature enhancement purposes. The Italian government had already processed the LiDAR point cloud data at 1 m resolution (lower than other recent applications of LiDAR; Pranzini, 2007), yet it proved sufficient for our processing needs. We applied sun shading to the DEMs and an 11x11 high pass filter prior to imagery assessment.

The landscape surrounding Portus is generally composed of cultivated fields, low lying grass, and shrubbery, with its main period of cultivation running in spring and during the summer. The July 2010 Geoeye-1 imagery showed evidence of ongoing farming and harvesting, while the September 2011 WorldView-2 imagery showed the same fields as fallow with young grasses. This proved key in identifying the additional buried remains in the WorldView-2 imagery: while the 2010 summer had higher levels of precipitation initially, it had normal temperature indexes for July–August. Europe had high temperatures for the end of the 2011 summer, with the overall grasses growing quickly following the harvest period.

#### 4. Results of the pilot study

Processing the Geoeye data revealed a number of features. These included a linear anomaly immediately to the east of the Tiber formed of two parallel linear anomalies some 65 m apart and over 180 m in length, which we initially interpreted provisionally as

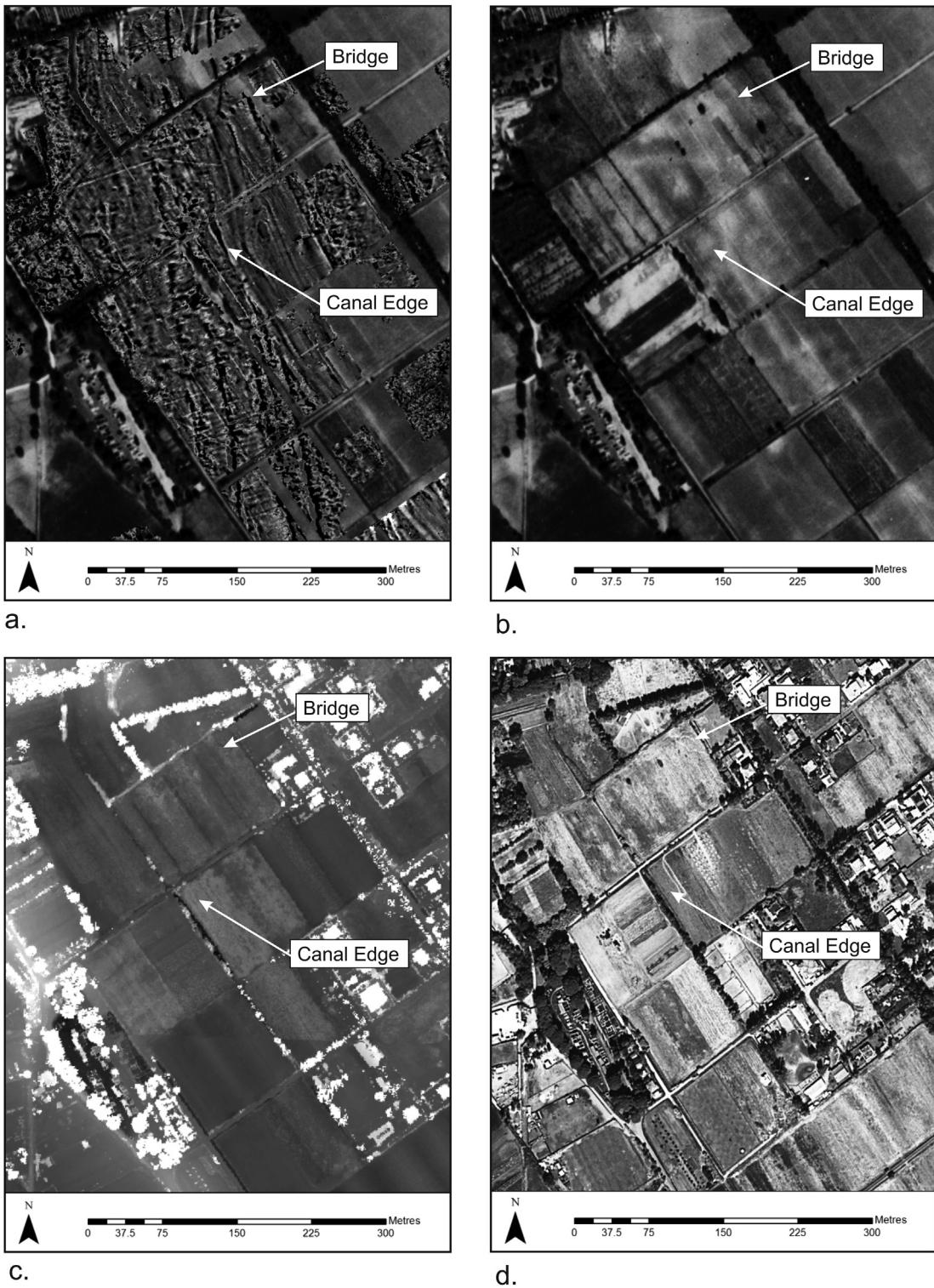
some kind of canal or channel. The WorldView-2 data revealed additional features. A linear feature emerged, 230 m in length, that appeared to be a hitherto undiscovered road running from east to west across the site of the *statio marmororum*, or ancient marble yards, to the south of the Fiumicino Canal (*Fossa Traiana*) immediately to the south of Portus on the Isola Sacra. Geophysical confirmation of this feature could aid in understanding how the people of Portus imported marble destined for Rome, stored it, and subsequently transhipped it on to river boats. Two kilometres to the south of this feature, close to the north bank of the Tiber opposite Ostia, analysis of the WorldView-2 data revealed a c. 100 m long feature. It belonged to some kind of large building that complements recent geophysical evidence for the existence of several large warehouses in this area (see below). This emphasizes the significance of the north bank of the Tiber to the commercial life of Ostia.

Another potentially very important discovery included an ovate feature 43 m E–W by 47 m N–S in size, lying between the main area of the port and the Tiber to the east. It has outer and inner rings separated by 8 m, and two gate-like features measuring 8 m × 7 m located on the easternmost and westernmost structure “entrances”. Its plan has a close resemblance to that of an amphitheatre, and if future geophysical work proves this to be the case, then it would be the first definitely attested amphitheatre at either Portus<sup>4</sup> or Ostia. Large monumental structures surround the feature, while a 1 km road running from the Tiber through modern cultivation bisects the eastern and western “gates”, showing that the structure may have existed as part of a larger ritual landscape.

LiDAR data revealed the presence of part of a 35 m wide platform very close to the recently identified site of the Pharos. It ran from north-west to south-east on a different alignment to that of modern buildings, but one which makes topographic sense given archaeological knowledge of the position of the north and south moles of the Claudian basin. The SRS and LiDAR data also revealed numerous additional archaeological features of significance either in areas where we already had conducted magnetometry surveys, or where we had not considered surveying due to the nature of the landscape. The SRS results proved that a dry summer is not the only optimal time to conduct SRS analyses in landscapes with diverse geological and soil conditions. Archaeologists need multiple types of SRS data from different years and months, with a clear understanding of local growing patterns that can optimize feature detection.

The combined geophysical survey techniques used at Portus provided a detailed and nuanced dataset, while the massive expanse of terrain comprising the hinterland of the port meant that magnetometry provided the only real option for total high resolution coverage of the entire area. A SRS program allows the integration of multiple datasets and different data forms, making it possible to map previously unknown new features in complex geological zones. A comparative analysis of remotely sensed data allowed us to assess the compatibility of ground survey data with air photography and satellite imagery, which varied in their extent and seasonality. The project magnetometer survey (measuring 0.5 m by 0.25 m per reading) closely matched the 0.5 m Geoeye and WorldView data. The aerial photography data generally had a submetre resolution. Many archaeological anomalies appeared for particular areas in the RAF and USAF imagery from 1943 to 44, including the Claudian Canal, and associated trackways to the east of Portus. No evidence for the canal traversing the Isola Sacra from Portus to Ostia Antica was visible in these images, whereas a single

<sup>4</sup> While a slightly smaller “amphitheatre-shaped” building or Ludus was discovered during excavations at the *Palazzo Imperiale* at Portus (Keay et al., 2011: 78–80 and Fig. 5.12).



**Fig. 6.** Composite images of the area of the channel on the Isola Sacra, showing a. the magnetometer survey, b. the 1943 air photograph, c. the LiDAR data and d. the satellite imagery.

swath of data from the Italian Aeronautica Militare from 1957 indicated the presence of the large canal (Fig. 6) running from north to south across the Isola Sacra, also mapped in the magnetometry results (Germani et al., 2011).

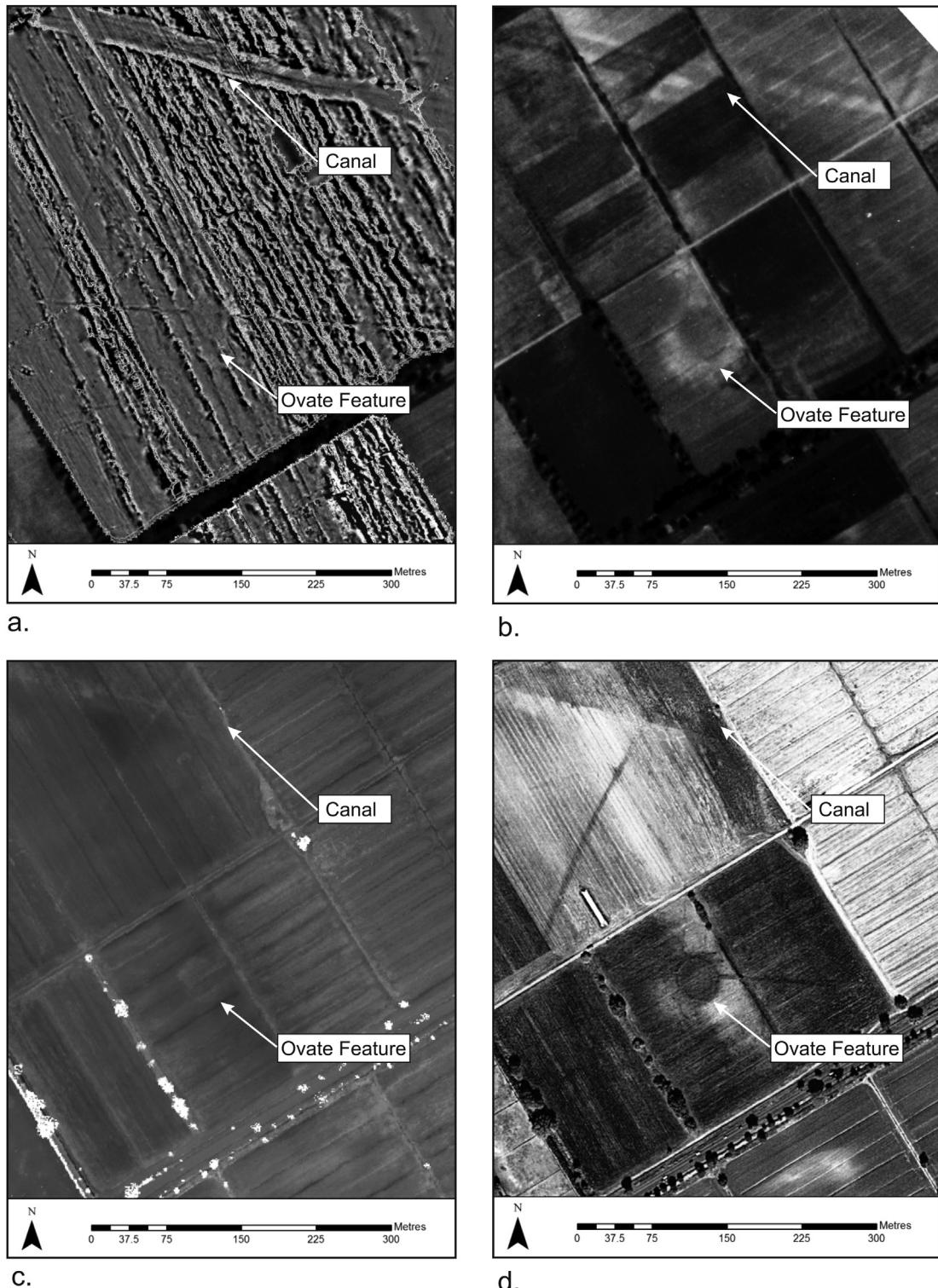
To the east of Portus, the satellite and aerial photography detected the course of roads and the extent of tombs whose

existence was verified by targeted geophysical survey. However, an assessment of the aerial photographs did not reveal the oval shape of the structure to the east of the port (Fig. 7), although it did reveal a rubble spread at this point. The eroded or scarped nature of the terrain during the formation of this structure actually created a uniform area in the magnetometer survey results, rather than the

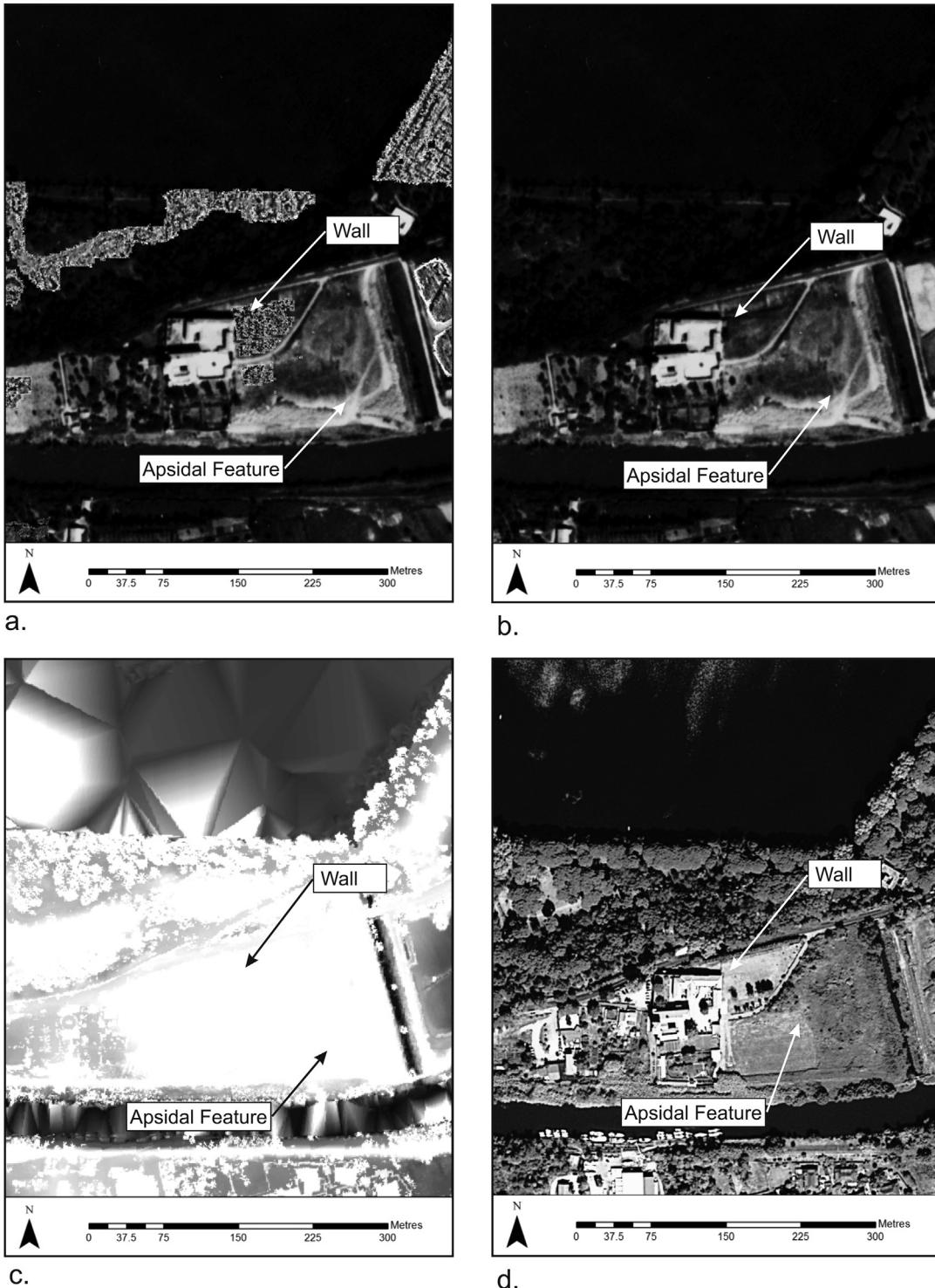
feature being highlighted in the geophysics. The area around the Episcopio, between the Trajanic Basin and the Fiumicino Canal, relied more heavily on the geophysical survey (Fig. 8). The satellite imagery showed a possible apsidal feature to the south-east of the Episcopio and some faint linear anomalies to the east. GPR survey of the area revealed a strong and broad linear anomaly adjoining the north wall of the Episcopio, and suggested a continuation of the late

fifth century AD defensive wall of Portus. The Episcopio, which incorporates early Imperial standing walls, may have therefore formed an integral part of the late antique defences along the line of the Fiumicino Canal (Fig. 9).

The two survey areas along the line of the Via Flavia demonstrated the limitations of the magnetometry and GPR. Although the line of the road appears in both sets of results, the satellite imagery



**Fig. 7.** Composite images of the area to the east of Portus, showing a. the magnetometer survey, b. the 1943 air photograph, c. the LiDAR data and d. the satellite imagery.



**Fig. 8.** Composite images of the area of the Episcopio, showing a. the magnetometer survey, b. the 1943 air photograph, c. the LiDAR data and d. the satellite imagery.

most clearly represents the presence of the road make up and tombs located along either side of the road. The magnetic signature of the wind-blown sand dune deposits over this area (along the line of the ancient coast) masked the response from the archaeology to the magnetometer survey, while the robbing of sections of the road surface in antiquity precluded it from generating a strong signal in the GPR results. The variable moisture content of the deposits facilitated their representation as areas of distressed vegetation in the satellite imagery. In the zone along the right bank of the Tiber

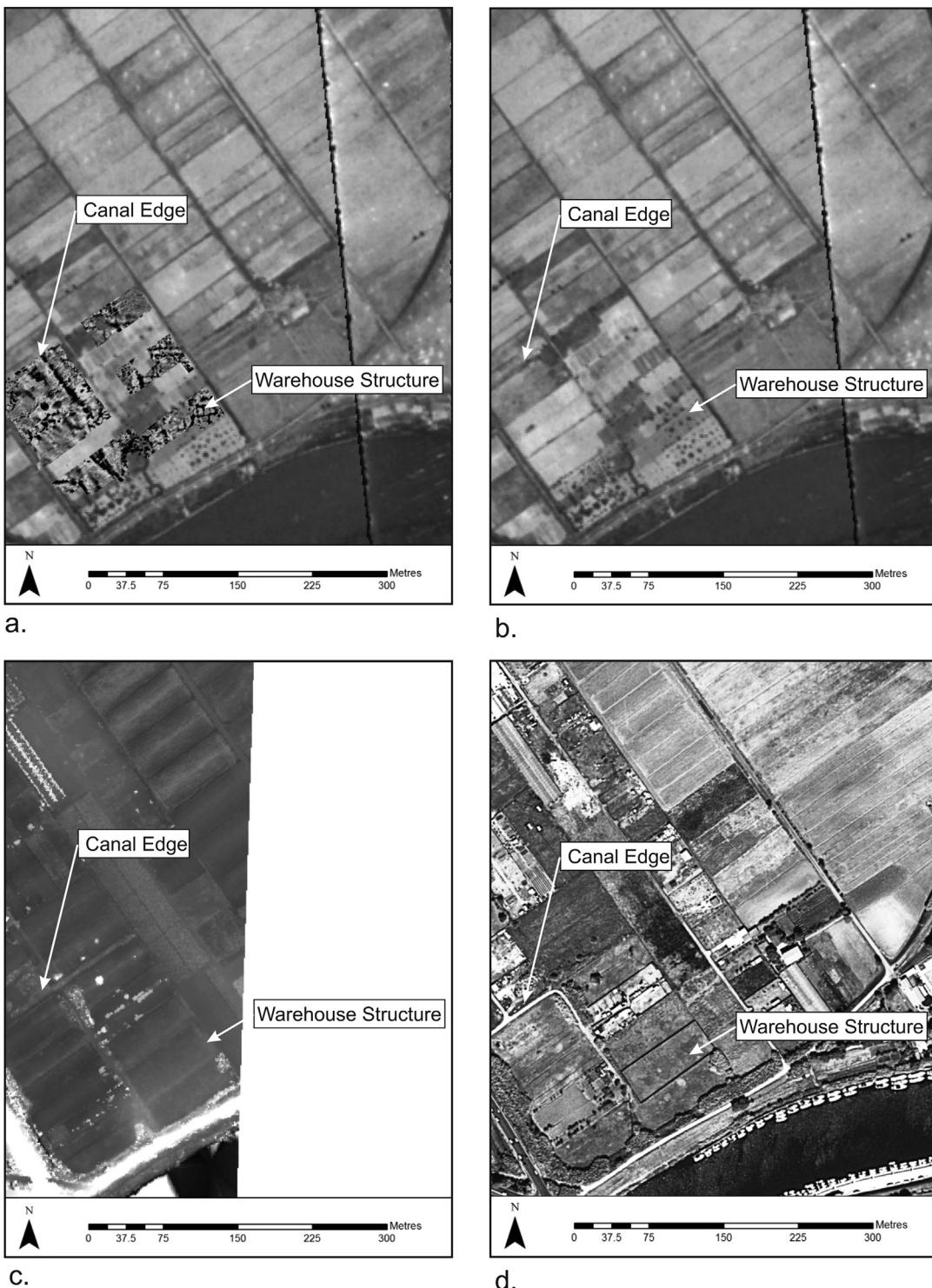
opposite Ostia (Fig. 10), a magnetometer survey of the area in which the satellite imagery had shown a significant linear anomaly, revealed a line of substantial rooms. Earlier geophysical survey in land to the east by the Portus Project shows that this may have belonged to a large rectangular warehouse with central courtyard, similar in plan to the *Grandi Magazzini* at Ostia, and that it was one of several similar buildings in the same region (Fig. 11), showing traces of a large complex of warehouses overlooking the Tiber to the north of Ostia. Comparison with the satellite imagery did not



**Fig. 9.** Image showing results from the GPR survey at the Episcopio, indicating the possible extension of the defensive port wall continuing to the east of the substantial extant remains of the Episcopio.

aid interpretation, as it revealed few detailed components of the features due to the cover of overlying sands and sediments and the result of later ploughing. At the same time, however, the fired brick and tile of the structures responded well to the magnetometer survey.

While SRS analysis prior to survey on the ground provides a cost-effective method of allowing targeted ground survey, magnetometry and GPR survey frequently locate archaeological features and deposits which do not appear in the SRS which include many of the Isola Sacra features, including the principal canal



**Fig. 10.** Composite images of the area to the north of the Tiber near Ostia, showing a. the magnetometer survey, b. the 1943 air photograph, c. the LiDAR data and d. the satellite imagery.

across the area, the system of smaller channels and land subdivisions, and significant structures in the area to the north of Ostia Antica. The nature of archaeological remains must be assessed from the SRS, but also extensive ground-based survey should expand on the pattern of anomalies represented therein.

## 5. Discussion

The integration of the Geoeye-1 and Worldview-2 satellite imagery with the existing and new geophysical survey data has broadened our knowledge of the presence, extent, and nature of



**Fig. 11.** Image of the Portus Project magnetometry survey to the north of the Tiber showing the presence of a defensive wall and warehouses associated with Ostia. This survey was undertaken in 2011 (Germoni et al. forthcoming).

buried known and newly discovered archaeological features associated with Portus. The integrated data identified hitherto unknown elements of the port complex infrastructure, including a stretch of the late antique defensive wall not apparent in the geophysics. The hinterland showcased the scientific benefits of the SRS analysis. Even though the 1998–2006 geophysical survey succeeded in identifying a range of hitherto unknown features (Keay et al., 2005), particularly in the open area lying between the Trajanic basin and the Tiber, it did not identify all potential features. The SRS discovery of the amphitheatre-shaped structure represents an important reminder of geophysical survey limitations. While not directly visible in the magnetometry, discontinuities in the underlying geological anomalies can be explained in terms of a buried structure with the hindsight offered by the SRS data. Other structures and man-made features did not appear in the satellite imagery, likely due to its spectral and spatial limitations. Magnetometry and SRS may also have missed features detectable only via GPR.

The strategy of integrated data analysis shows how the different structural materials and formation processes at Portus and in the surrounding landscape accentuate or limit the responses of different survey methods (Table 2). The spatial and quantitative integration of different datasets provided the team with the most significant results. The general background of alluvial deposits and magnetically enhanced bands of material across the delta provide a generally uniform background to the fired brick and tile, basalt and tufa structures of the port. However, where wind-blown and alluvial deposits of high magnetic signature obscure the results of magnetometry, the satellite imagery and GPR survey provide a clearer indication of buried structures. No single technique on its

own is sufficient to provide a full picture of the complex buried landscape of a major port like Portus, or indeed any major Classical site. An appropriate suite of survey detection techniques need to be used in concert, with the choice being dependent upon the character, scale and extent of the site and its geomorphological background.

Further enhancement of the current methodology will help us to refine the comparative strategy to gain a greater understanding of the landscape. Currently the Portus Project team are producing the final digitized interpretation of the geophysical survey results, and utilising the existing results there are plans to cover a greater area of the port complex using GPR to complement the magnetometry. Further satellite imagery from the Tiber delta is also forming part of a study of archaeological sites and delta

**Table 2**

Archaeological features at Portus as identified (or not identified) but the various remote sensing technologies reviewed in this paper.

Key Discovery	Magnetometry	ERT/GPR	LiDAR	Air photography	Satellite imagery
Transverse Canal from Portus to Ostia	Yes	No	No	Yes	No
Amphitheatre to east of Portus	No	No	Yes	Yes	Yes
Warehouses to north of Tiber	Yes	No	No	No	Partial
Defensive Wall at Episcopio	No	Yes	No	No	No
Lighthouse	No	No	Yes	No	Yes

geomorphology further afield. In addition the conducting of bore-hole surveys relating to the geophysics and satellite data across the port complex is taking place with colleagues from the University of Lyon (Keay et al., 2014; Salomon et al., 2010, 2014) aiding the dating of substantial deposits and features found in the geophysics and SRS data. It is hoped that a campaign of hand augering of features in the landscape will help provide further information on the chronology, nature and formation of features.

## 6. Conclusions

New techniques have brought about a transformation in our approach to Classical archaeology over the last thirty years. The adoption of aerial photography, field survey and geophysics as relatively efficient and rapid mapping tools for ancient settlement patterns and, more recently, the layout of larger urban sites, has proved indispensable in the study of large sites or historic landscapes. SRS analysis provides a further research dimension previously untested on a large urban Roman landscape, and as a key multi-scalar technique enables archaeologists to contextualize and complement other technical approaches within even larger landscapes. The application of these complementary techniques at Portus has highlighted the presence of a number of structures and features associated with the port infrastructure, including an amphitheatre-shaped structure to the east of the port, the presence of a possible channel or canal to the east of Portus, and the part of a warehouse or defensive wall to the north of the Tiber associated with Ostia Antica. The integration of SRS, aerial photography and geophysics is thus providing an increasingly clear image of buried features, and a general understanding of the response to different types of technique based on the types of material present. The success of locating brick and tufa structures with magnetometry, and the use of air photographic and satellite imagery in locating broader geomorphological features or structures comprising travertine or other non-ferrimagnetic materials has been demonstrated. However there is still much to understand about the responses of different kinds of building material, or their surrounding geological contexts.

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