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REVISITING COSA (ANSEDONIA, ITALY): CONTRIBUTIONS OF SAR-X IMAGES FROM THE PAZ SATELLITE TO NON-INVASIVE ARCHAEOLOGICAL PROSPECTING

REGRESO A COSA (ANSEDONIA, ITALIA): CONTRIBUCIONES DE LAS IMÁGENES SAR-X PROCEDENTES DEL SATÉLITE PAZ EN LA PROSPECCIÓN ARQUEOLÓGICA NO INVASIVA

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Highlights:

- Some archaeological results obtained using SAR-X images received through the PAZ satellite and applied to a part of what was called *Ager Cosanus* are shown in this article.
- The study has been completed with the analysis of multispectral images TripleSAT and Sentinel-2A and the historical aerial photos from 1944 and 1954.
- The possibilities of using PAZ images treated multi-temporally as a high-resolution panchromatic image applicable to multispectral optical images of the type Sentinel-2 were tested.

Abstract:

Some archaeological results are shown in this article, which have been generated from the use of Synthetic Aperture Radar (SAR)-X images obtained from the PAZ satellite and applied to part of what was called *Ager Cosanus*, that is, the territory of the city of Cosa, which was one of the first maritime colonies of Rome in the heart of Etruscan territory. Our study has been carried out mainly based on previous works in which a set of images was used to improve the quality of the resulting image, reducing the noise caused by the speckle of the radar images and maintaining the quality of the spatial resolution that can be obtained from these images (1.25 m/pixel). More specifically, a set of images obtained between 2019 and 2021 was used. The study has been completed with the analysis of multispectral images TripleSAT and Sentinel-2A, the historical aerial photos taken from 1944 and 1954, and the use of the historical cadastre of Tuscany, prepared at the beginning of the 19th century. As an addition, the Digital Terrain Model (DTM) Light Detection And Ranging (LiDAR) of the Region of Tuscany was used, on which various functions of the Relief Visualization Tool (RVT) programme have been applied, complementing or contrasting the results. It can be confirmed that the multi-temporal treatment of SAR PAZ images provides better results than an individualised analysis of the image. Finally, it is of great interest to verify the results of studies using new technologies, where it was previously possible to resort only to prospecting on the ground and to analogical aerial photography in black and white. In this case, the Sinistra Decumano I (SDI) structure was seen, which Castagnoli observed in the aerial photography, but of which he only located materials on the ground and it was visualised both in individualised PAZ images and in Sentinel-2.

Keywords: remote sensing; PAZ; synthetic aperture radar (SAR)-X; multispectral images; archaeology; light detection and ranging (LiDAR)

Resumen:

Este artículo muestra algunos resultados arqueológicos generados a partir del uso de imágenes SAR-X obtenidas a través del satélite PAZ y aplicadas a una parte de lo que se denominó *ager cosanus*, es decir, el territorio de la ciudad de Cosa, que fue una de las primeras colonias marítimas de Roma en el corazón del territorio etrusco. Nuestro estudio se ha realizado principalmente a partir de trabajos previos en los que hemos utilizado un conjunto de fotografías para mejorar la calidad de la imagen resultante, reduciendo el ruido provocado por el moteado de las imágenes de radar y manteniendo la calidad de la resolución espacial que se puede obtener de las mismas (1.25 m/píxel). En concreto, se ha trabajado con un conjunto de imágenes obtenidas entre 2019 y 2021. El estudio se ha completado con el análisis de imágenes multiespectrales TripleSAT y Sentinel-2A, las fotos aéreas históricas tomadas a partir de 1944 y 1954, y la utilización del

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catastro histórico de la Toscana, elaborado a principios del siglo XIX. De forma complementaria, se ha trabajado con el Modelo Digital del Terreno (MDT) LiDAR de la Región de Toscana, sobre el que se han aplicado diversas funciones del programa Relief Visualization Tool (RVT), complementando o contrastando resultados. Podemos confirmar que el tratamiento multitemporal de las imágenes SAR PAZ proporciona mejores resultados que un análisis individualizado de la imagen. Por último, resulta de gran interés el comprobar cómo la utilización de imágenes PAZ y Sentinel-2A permiten la revisión de resultados de estudios anteriores, en los que sólo era posible recurrir a la prospección sobre el terreno y a la fotografía aérea analógica en blanco y negro, como en el caso que aquí se presenta, donde se analiza una de las estructuras de parcelario romano, la *Sinistra Decumano I* (SDI) del *ager cosanus,* localizada y publicada por Castagnoli en 1993.

Palabras clave: teledetección; PAZ; radar de apertura sintética (SAR)-X; imágenes multiespectrales; light detection and ranging (LiDAR)

1. Introduction

The analysis and results obtained from a set of Synthetic Aperture Radar (SAR) images captured by the PAZ satellite is presented in this paper, applying it to non-invasive archaeological prospection and combining it with other analysed sources, such as multispectral images, historical aerial photographs or XIX century cadastres.

The area under study (Fig. 1) corresponds to the so-called *Ager Cosanus*, the territory of the Roman colony of Cosa (Ansedonia, Italy). This city was founded in 273 BC by Rome, with the legal status of a Latin colony. Its remains are located in the vicinity of what used to be the route of the Via Aurelia, the ancient Roman road that ran along the Tyrrhenian coast. The settlement's aim was to articulate and exploit an area located in the heart of the hinterland of the Etruscan cities of Vosinii and Vulci, confronting Rome in 280 BC and finally being subdued.

Figure 1: Location of Cosa and its territory. Source: ESRI Satellite.

Its objective was also to control the coast through notable and recognised port facilities, such as *Portus Cosanus*. An intermittent inhabitation of Cosa is demonstrated from the period of founding until the beginning of the 5th century AD, with a period of special apogee that can be set between the beginning of the 2nd century BC and the first quarter of the 1st century BC. From the end of the 2nd century AD the city entered a phase of frank decline and economic contraction despite being an administrative centre during the 3rd century AD. This progressive process of crisis culminated in the definitive abandonment of the city towards the beginning of the 5th century AD. Still, signs of feeble resettlement during the Byzantine period (6th century AD) can be observed: the Arx, that is, the sacral area located in the highest area of the site was fully restructured and fortified to house a military garrison, while in the forum a few habitat structures were concentrated around a Christian church that had stood on the ruins of the old forensic basilica. This organisation was dismantled by the Lombard occupation and Cosa was transformed into a poor rural settlement that would survive in Carolingian times and that, during the 10th century, would be endowed with a castle located on the elevation that rises at the eastern end of the ancient city. The definitive abandonment took place in the 14th century when the castle was destroyed by the Republic of Siena. Cosa did not just function as an intramural organised urban centre on top of Ansedonia hill. It is necessary to also include in it a port area on the coast and at the foot of the hill to the southeast, Portus Cosanus, as well as a suburb located in the lower part after the port, to the east of the city, Succosa (or Subcosa) (Roca, Madrid, & Celis, 2013).

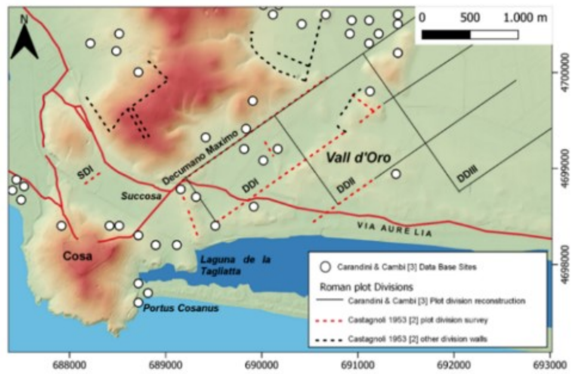

Figure 2: Location of the Cosa site. Sources: LiDAR DEM 2x2 MATTM – LiDAR aree interne Tuscany region.

On the territory (Fig. 2.), the colony was organised by structuring the distribution of land through a system of parcelling (centuriation) based on rectangular modules of 568x1136 m., or the equivalent in Roman measurements, 16x32 *actus* (Castaglioni, 1993. 785-786; Carandini & Cambi, 2002, 121-123). The study region corresponds to the area that includes the hill on which the city was founded, *Portus Cosanus*, *Succosa* and the annexed territory. In this area, the so-called Vall d'Oro, located northeast of the colony, previous studies (Carandini & Cambi, 2002; Castaglioni,1993) had already revealed the structure of the centuriation system through traces of walls and delimitation ditches that were still visible in the aerial flights of 1944 and 1953. That indicates the system used by Rome to structure the division and organisation of lots among settlers. In particular, Castagnoli (1993) had identified one of the two main axes of the division system, the *Decumanus Maximus*, and several of the secondary axes: Sinistra Decumano I (SDI), Dextra Decumano II (DDI), and Dextra Decumano III (DDII). In other words, SDI and DDI would be the first secondary axis, on the left, and the first on the right, of the Decumanus Maximus. The latter would be a main axis. that would serve at the time as a connection between Cosa and Via Aurelia with the interior, more specifically with the colony of Saturnia founded in 183 BC (Carandini & Cambi, 2002;164). The fieldwork started in 2013 within the framework of the archaeological excavation campaigns in the Roman colony of Cosa directed by Dr. Mercé Roca, then director of the Spanish mission. At that time, the project intended to establish the foundations for a review of the territory called *Ager Cosanus* using above all non-invasive techniques through remote sensing. A pedestrian exploration was carried out on the ground to document some of the sites and structures visible at that time, in anticipation of continuing the work in successive campaigns. The first (and only) campaign focused on a field survey in the Vall d'Oro, in the Tagliatta area, where *Portus Cosanus* was located (Fig. 3g) and in Tombole de la Feniglia. To support the photogrammetric work, based on the coverage of high resolution aerial photography taken with air hot ballon in previous years and with the first experiments with UAV (Unmanned Aerial Vehicle) at the site in the next attempts, a Global Navigation Satellite System (GNSS) Real-Time Kinematic (RTK) Positioning System was also carried out for topographic survey (Fig. 3b) (Fiz et al., 2022; Roca & Fiz, 2013). More specifically, in the Vall d'Oro in June 2013, a reconnaissance on the ground was carried out of the main Roman farms, such as the Villa delle Colonnette (Fig. 3a, Fig. 4a,b), the Villa de Settefinestre (Fig. 3d, Fig. 4c,d), and Casale Marotti (Fig. 3c) and the still visible structures of the delimitation walls of the aforementioned agrarian division system were documented (Fig. 3f,e, Fig. 4). These Roman villas, defined as *Ville con fronte a torrette*, bear the peculiar characteristic of having a series of turrets as part of one of the front walls delimiting property. With a diameter of only 120 cm, they are decorated with niches with an ornamental function serving as buttresses for the terraced walls (Calastri, 2004; Quilici & Quilici, 1978). Unfortunately, in December 2014, the mournful demise of Dr. Roca, director of the mission, occurred, preventing the continuity of the fieldwork on the ground, and leaving the review project inconclusive.

It is worth mentioning the exhaustive and exemplary work on the landscape of the so-called *Ager Cosanus* of Andrea Carandini and Franco Cambi (2002), which had been started in the 70s of the last century, with the results published in 2002. On the other hand, the works published by the Laboratory of Landscape Archaeology and Remote Sensing at the University of Siena can be found locally within Tuscany. The publications include the aerial coverage carried out between 2000 and 2005 to map, photograph and monitor for heritage conservation the monuments and archaeological elements in the landscape from prehistory to the Middle Ages in the province of Grosseto (where Cosa is located), Siena and Livorno (Campana, Francovich, Pericci, & Corsi, 2006). In addition, the same team carried out the first studies with high resolution multispectral images, applying them to the location of archaeological sites in southern Tuscany (Campana, 2002; Campana, Dabas, Marasco, Piro, & Zamuner, 2009; Campana & Francovich, 2006). It was in the mid-1980s that the first geoarchaeological studies with SAR platforms began to be carried out McCauley et al., 1982; Blom et al., 1997; Adams, 1980; Sever & Irwin,2003). At that time, the limit in the average resolution of the sensors reduced the work to an analysis of still preserved monuments, cultural landscapes, paleo-landscapes and canal systems. With the turn of the century and the launch of the TerraSAR-X and COSMO-SkyMed platforms in 2007, access to high resolution data became possible. This improvement allowed the almost immediate use of these platforms in the detection of archaeological remains.

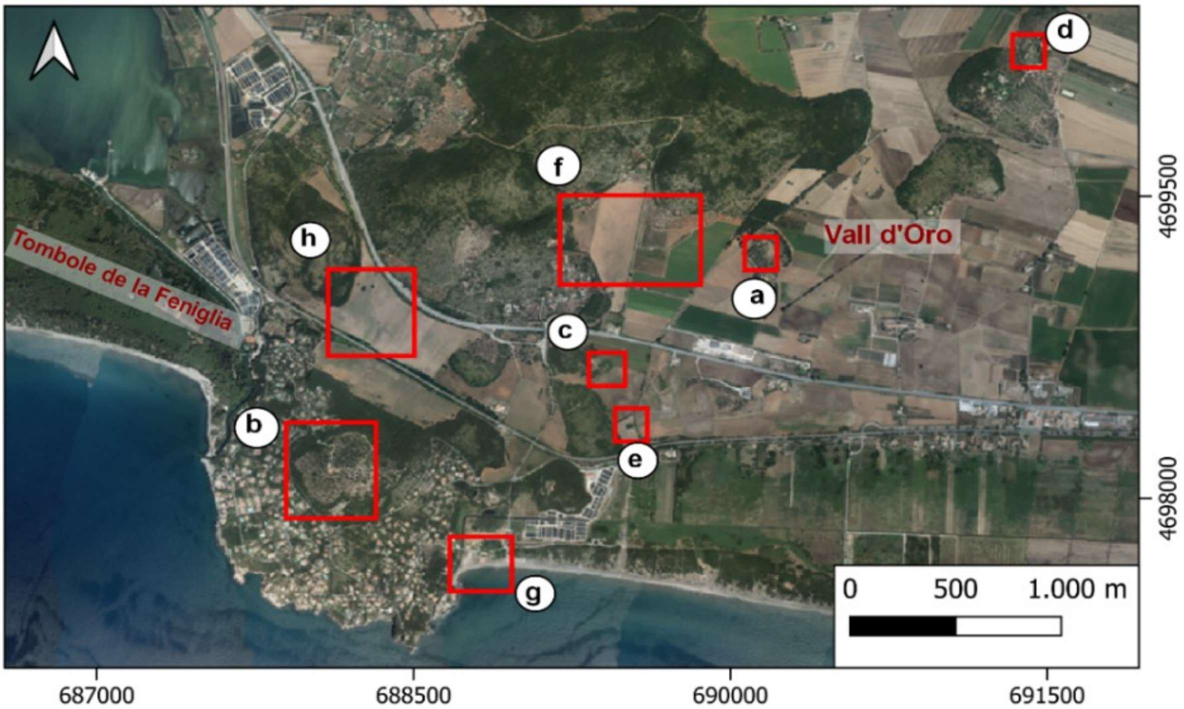

Figure 3: a) Villa delle Colonnette; b) Cosa; c) Casale Marotti; d) Villa of Settefinestre; e) Delimitation wall remains; f) Delimitation remains of the *Decumanus Maximus*; g) *Portus Cosanus*; h) *Area where the SDI was located*. Source: WMS OFC 2019, 20 cm, 32-bit RGB.

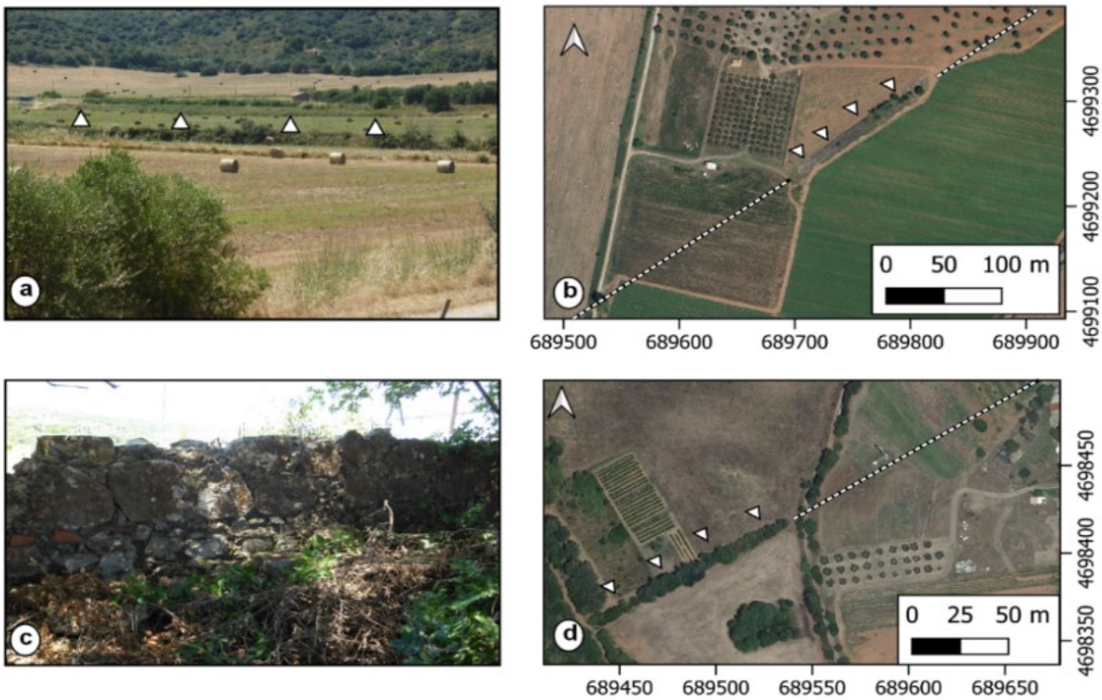

Figure 4: a) Villa delle Colonnette; b) Villa de le Colonnette. A detail of a dolium used as a construction element can be seen in the enlargement; c) Villa of Settefinestre. The same type of turrets on the walls delimiting the town can be seen in the enlargement; d) Villa de Settefinestre: terraced walls of the villa.

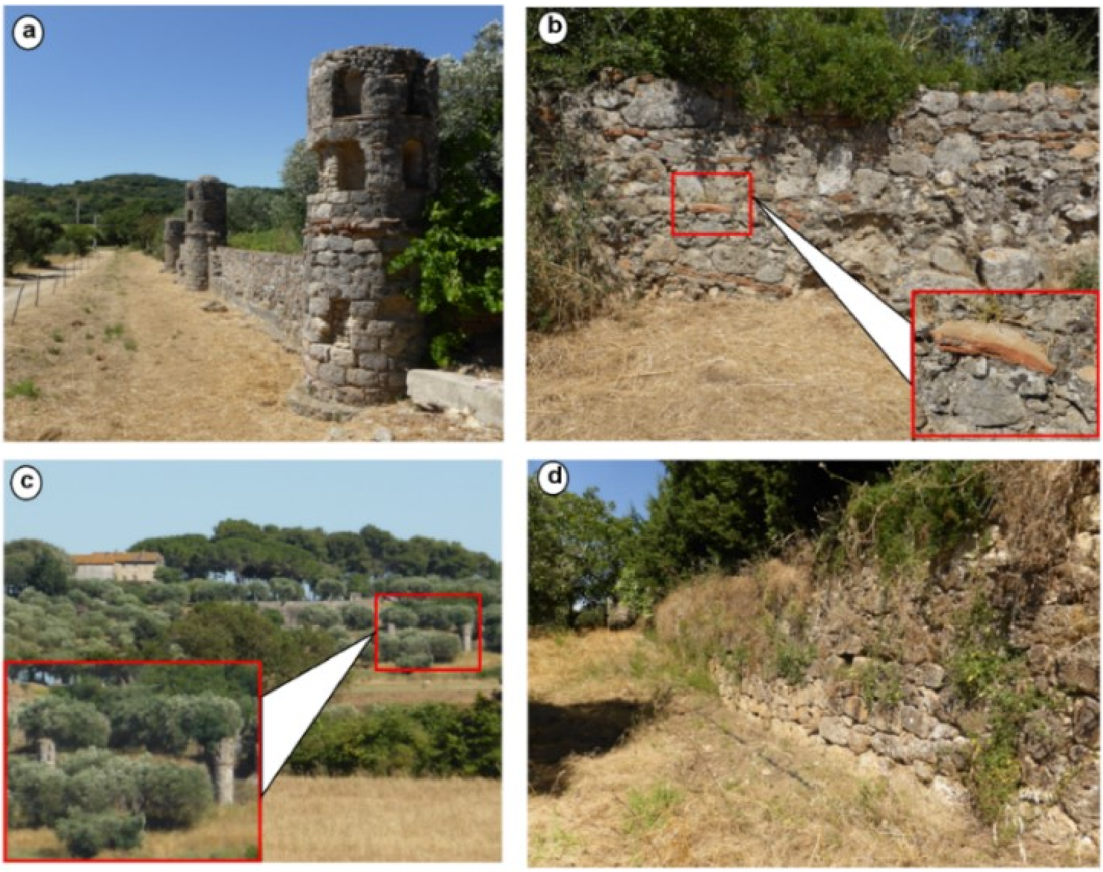

Figure 5: a) Remains of the Decumanus Maximus still visible on the ground; b) Location of the remains of the Decumanus Maximus; c) Remains of one of the delimitation walls of the centuriation system. Image sources: WMS OFC 2019, 20 cm, 32-bit RGB.

However, in terms of the band used, the penetration capability is very limited in the X-band compared to other bands, such as the L and C bands (Lasaponara & Massini, 2013;71-75). The first element to take into consideration is that both PAZ and TerraSAR-X work in the X band.

The work carried out by Monterroso and Martínez (2018) on the territory of the Roman city of Mellaria (Cordoba, Spain) demonstrated the effectiveness of these sensors when applied for the detection of large old infrastructures. The use of SAR sensors allowed the detection of sections of the Roman road under cultivated fields. The humid climatic conditions increased the sensitivity of the sensors, thus finding also remains of medieval roads, paved with gravel, and built without drainage elements. The latter also facilitated their detection as the accumulated moisture was retained in the soils overlying these infrastructures. These results allowed them to conclude that conditions of high humidity and rainfall in cultivated fields improved the results obtained with SAR. On the other hand, in uncultivated fields, it was much better to perform analysis with multispectral sensors (Monterroso & Martínez, 2018). In February 2018, the PAZ satellite was launched into orbit. This platform, managed by Hisdesat, is equipped with the SAR sensor (Hidesat, 2021).

This sensor consists of an X band SAR radar, with four imaging modes Spotlight, HR (High Resolution) Spotlight, StripMap and ScanSAR and several types of polarisations: single and dual. A set of X-Band SAR images was accessed through a call for opportunity from the *Instituto Nacional de Técnica Aeroespacial* (INTA). The Spotlight product (resolution of 1.25 m/pixel) was mainly used (Fiz, Cuesta, Subias, & Martin, 2021).

On the other hand, the use of various non-invasive techniques should be highlighted in these remote sensing works on archaeological remains (Kadhim, Abed, Vilbig, Sagan, & DeSilvery, 2023; Abate et al., 2023; Villarejo & Delgado, 2023).

Table 1: Technical information

Source	*Dates*	*Spatial Resolution*	*Description*
PAZ Spotlight	21/08/2019; 01/09/2019; 12/09/2019; 23/09/2019; 04/10/2019; 27/07/2020; 18/08/2020; 29/08/2020; 03/07/2021; 14/07/2021; 25/07/2021; 05/08/2021; 16/08/2021;19/09/2021	1.25 m/pixel	Polarisation: HH Ascending
PAZ Spotlight	23/08/2022	2.24 m/pixel	Polarisation: HH VV Ascending
Triple SAT 2	02/01/2020	PAN 0.8 m/pixel MS 3.2 m/pixel	
Sentinel-2	18/04/2020; 8/04/2020	10 m/pixel 20 m/pixel 60 m/pixel	
LiDAR	2008 flight [28]	2 x 2 m	DTM-LiDAR files (.asc format)
RAF Aerofototeca Nazionale	Flight in 1944. Analogue photography RAF_1944_135_447_3006_0_0 RAF_1944_135_448_4005_0_0	0.59 m/pixel	Georeferenced images
WMS Geoscope and Castore, Region of Tuscany (Sistema Informativo Territoriale ed Ambientale)	OFC 2019 20cm – 32-bit colour – RGB. [29] OFC 1954 (volo GAI) [30] Castore: Cadastre s. XVIII y XIX. [31]		WMS link.

2. Materials and methods

The SAR images of PAZ, the DTM of the Region of Tuscany, TripleSAT and Sentinel-2 multispectral images were used on this second work area (Table 1). On the other hand, the 1944 flights of the Royal Air Force (RAF) in Italy during World War II from the Archivio Aero fototeca Nazionale acquired in 2013 were used to contrast results, as well as the flight in 1954 OFC 1954 (volo GAI) which was available through the Servizio OGC type WMS produced by the Region of Tuscany (Geoscopio). The geometric cadastre of Tuscany, prepared for the entire territory of the "Granducato di Toscana" between the end and beginning of 18th and 19thcenturies was accessed using the aforementioned server, called CASTORE (Catasto Storici Regionale) (Grava, Trevisani, Sassoli, Peri, & Lucchesi, 2017).

Regarding the archaeological data, the georeferenced database of sites published by Carandini and Cambi (2002) was used above all, which was incorporated into a simple Excel table as database in order to integrate it into a GIS prepared with all the materials.

The SAR images used are of HH and HV polarisation. The first ones were taken in the months of July to October 2019, 2020, and 2021. The second ones were taken in August 2022. The choice of these seasonal periods was due to the fact that previous studies with SAR images had obtained better results in arid areas (Wiig et al., 2018; Elfadaly, Abate, Masinni, & Lasaponara, 2020). For that reason, the largest number of images was taken in the course of the summer and early autumn seasons, i.e., with a climatology of high temperatures and low precipitation. The TripleSat satellite, launched in 2015 (Wen et al., 2017), provided one panchromatic band at 0.8 m/pixel resolution and four bands at 3.2 m/pixel (NIR, Red, Blue, Green). There are two reasons for having used two different polarisations in the PAZ images. In the first case, the HH polarisation was used due to the fact that the high resolution image (1.25 m/pixel) is only obtained in this band. In the second case, the images have a lower resolution (2.24 m/pixel), but allow working with two polarisation bands HH and VV, which in turn allows combining the bands visually, in a false RGB, as has been done in this study, and also the generation of vegetation indices (Ratha et al., 2019; Gonenc, Ozerdem, & Acar, 2019). This second application could not be developed in this study, leaving it for future applications. The acquisition of these multispectral images was intended to coincide with the Summer and Autumn periods. Finally, as will be explained later in the methodological section, tests were made to check the ability to use PAZ as a panchromatic image applied to medium resolution multispectral images, which Sentinel-2 can be used for. The Copernicus Sentinel-2 Constellation is composed of two satellites; Sentinel-2A launched in June 2015 and Sentinel-2B launched in March 2017. They both carry on board a Multi-Spectral Instrument (MSI) sampling 13 spectral bands, from visible to short wave infrared, with four bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolution (Boccia & Szantoi, 2020). For this work, various tests have been carried out with a selection of scenes from Sentinel-2A taken throughout the period be-tween 2020 and 2021.

The supplied PAZ radar images were processed mainly using the SNAP v. 8.0 (Sentinel Application Platform) of the European Space Agency (ESA), developed jointly by Brockmann Consult, Sky Watch and C-S. This programme was used in the analysis of the optical images TripleSat and Sentinel-2, as well as the free software QGIS v. 3.16.11 Hannover. This is an application under GNU GPLv2 licence, which has helped to visualise the results, superimposing and contrasting them with information from other layers.

The open-source software SAGA v. 7.9.0 (Software for Automated Geoscientific Analyses) was also used. This programme has a wide variety of filters and interpolation systems, as well as pansharpened functions for multispectral images, such as TripleSat. Researchers from the Department of Physical Geography in Gottingen and the Department of Physical Geography in Hamburg were the ones who initiated the development of SAGA.

In relation to the improvement of the Digital Terrain Models (DTMs), functions of the Relief Visualization Tools (RVT) programme v. 2.2.1 (Kokalj & Hesse, 2017) were applied. This product has been developed by a research group from the Slovenian Academy of Sciences and Arts in a project led by Žiga Kokalj. These techniques have provided spectacular results in revealing archaeological structures, becoming one of the indispensable elements in a non-invasive survey of the landscape. For this reason, the methodology and technique followed, was the one applied in works, such as the location of the structures of a medieval fortification in Basilicata (Italy) (Masini et al., 2018), the Samnite forts of Civitella (Longano, Italy) and the archaic and Hellenistic urban centre of Satricum (Lazio) analysed using SAGA functions (Garcia 2018), and the recording of archaeological remains in the Roman limes of Dacia in Porolissum (Romania) (Roman, Ursu, Lazarescu, & Opreanu, 2016).

2.1. SAR Sources: Techniques used

The individualised treatment of radar images (Fig. 6a) (Fiz et al., 2021), implied the application of filters to eliminate the speckle inherent in this type of image. However, the results obtained based on the workflow and speckle removal filters explained by Meyer (2019) and Monterroso and Martinez (2018; 304), were not as satisfactory as the joint use of multiple SAR images at different time points in the same study area, which can reduce speckle by providing images of greater clarity than when treating them individually. In another way, the method explained by Tapete and Cigna (2019;11-25) was used in Clunia, obtaining sharper images (Fiz et al., 2021) (p. 7, Fig. 3).

It was necessary to use the co-registration function in this process, which involves the creation of a stack of images, with one being the reference one, and the rest being subordinate ones. The programme then places (collocate function) samples from the subordinate bands in the reference band using their geographical position and an automated ground control point (GCP) selection. The multi-temporary speckle filtering function is then applied, using the Lee Sigma filter. From this point it is possible to perform statistical averaging operations that facilitate the generation of a final image, which is more accurate and sharper than that obtained from a single SAR image. This method has also been applied by Stewart (2017), focusing on several areas of Lazio (Italy) with COSMO-SkyMed images, and by the same author (Stewart, Oren, & Cohen-Sasson, 2018) on the archaeological site of Qasrawet (North Sinai) using TerraSAR-X images in that instance.

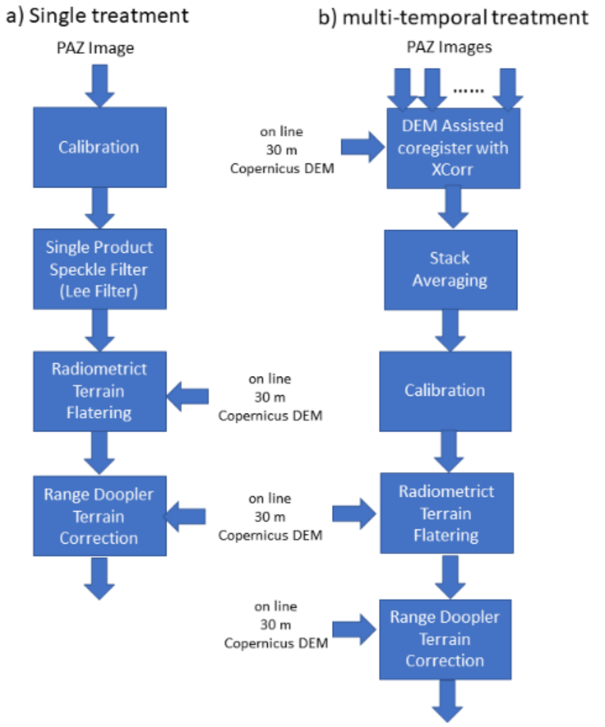

Figure 6: a) Single treatment b) Multitemporal treatment. From (Meyer, 2019)

However, a modification in the selection of the co-registration function was applied on this occasion (Fig. 6b), opting for the Digital Elevation Model (DEM) assisted coregister function, which relies on the DEM to perform the operation and that can be selected among various online DEMs. The selected one for this work was Copernicus DEM at 30 m/pixel. On the other hand, based on the results of the tests it is possible to conclude that the application of multi-temporary speckle filtering is not necessary if this method is applied, since the inherent speckle elimination process is solved in a satisfactory way.

2.2. Sentinel-2: Techniques used

One of the approaches marked as an objective was to check if it was possible to use the PAZ image resulting from the application of the multi-temporary treatment described above as a panchromatic source, from which to transform the resolution of Sentinel-2 optical multispectral images. It would be equivalent to having multispectral images, which by default are at 10, 20 and 60 m/pixel resolution, to one of 1.25 m/pixel. The use of high-resolution radar images to apply pansharpening functions on them had already been proposed by Klonus, Rosso, & Ehlers (2008) using a TerraSAR-X image as panchromatic and applying Ehlers fusion on Quickbird multispectral images. Treatment filters such as Frost or Lee had been applied to remove speckle and the authors concluded that it is possible to use the Ehlers fusion to enhance optical multispectral data with TerraSAR-X data. In addition, this type of fusion allowed a balance between the preservation of the colour and the enhancement of spatial resolution. At that time, Enhler's approach (2008) made it clear that the most advanced fusion systems implemented, presented colour distortion problems that ranged from brightness problems to complete changes in the spectral characteristics of the image bands of optical sensors.

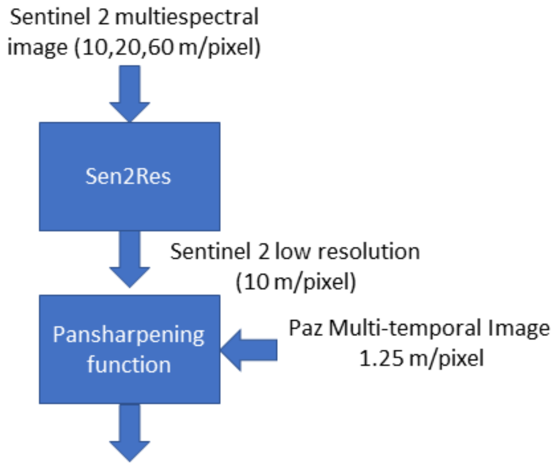

Figure 7: Sentinel-2/PAZ Pansharpening workflow

Taking these problems into account, it was necessary to apply the pansharpening functions provided by QGIS (simple Reaction Control System (RCS) pan sharpening operation; Bayesian; Local Mean and Variance Matching LMVM Pan sharpening) and SAGA (Colour normalised Brovey sharpening; Colour normalised spectral sharpening; Intensity, hue, saturation sharpening). The most appropriate one, which is Ehlers, could not be used, as this is the owner of commercial software (ERDAS).

However, the main scope of interest was to analyse the fusion-enhanced Sentinel-2 images with the intention of detecting anomalies that could be identified with archaeological structures. In this perspective, the process was carried out in two steps. The Sen2Res function of SNAP with the Sentinel-2 image itself was used for the first one. This function, designed by Nicolas Brodu (2017), takes the highest resolution bands, band dependent information (reflectance) separating the information that is common to all bands (geometry of scene elements). This model is then applied to unmix low resolution bands, preserving their reflectance, while propagating band-independent information to preserve the subpixel details. The result is that it allows all the bands of a Sentinel-2 image to be reduced to 10 m/pixel. The pansharpening functions were used in the second step: those provided for QGIS in the Orfeo toolboxes, as well as those incorporated by SAGA, using the PAZ image at 1.25 m/pixel resulting from the multi-temporal treatment as panchromatic and applying it to the Sentinel-2 optical multispectral image resulting from Sen2Res and at 10 m/pixel resolution (Fig. 7).

2.3. LiDAR: Techniques used

The first objective was to obtain the DTM files corresponding to our working area. These were downloaded from the SITA server-platform of the Tuscany Region (SIPT, 2023).

These DTM files were downloaded by sheets with a resolution of 2 x 2 m and are Creative Commons licenses. It was necessary to use the SAGA programme on these files (a total of 45) to obtain a single DTM file first. However, it was necessary to carry out two previous operations.

Lee filtering functions of the SAGA programme were applied first. This function allows the preservation of edges and removes mottling from the SAR images and also provides smoothing of the DTM. As a result, slope breaks and narrow valleys are preserved (Selige, Böhner, & Ringeler, 2006). This DTM presents problems of parallel stripes generating problems in the correct visualisation of the image. To eliminate this imperfection, SAGA's Striping function was applied (Oimoen, 2000; Perego. 2009).

After this pre-processing of the DTM, it was enhanced using various functions of the RVT programme (SkyView Factor, Openness Positive and Negative, Simple Local Relief Model, etc). This enhancement makes it possible to highlight possible anthropic landforms (terracing, land divisions, buried structures, etc.), as mentioned above.

3. Results

3.1. Explored areas

The focus was centred on the following areas for non-invasive exploration techniques: The Vall d'Oro, which include the Roman villa, mentioned above, such as the Villa delle Colonnette, the Roman parcel division elements in proximity to the colony of Cosa and anomalies detected in the PAZ images.

3.2. The Villa delle Colonnette

As already mentioned, this Roman villa presents a sequence of three terraces adjusted to the orientation of the centuriation of the territory and focused towards the Southwest-Northeast. The Villa delle Colonnette belongs to a set of monumental Roman villas in the area that stand out precisely because of the delimitation walls with small turrets that would make them look like military fortresses from a distance (Carandini & Cambi, 2002; 11). They also stand out due to the large terraces implemented, creating scenographic and panoramic spaces elevated above the plain.

The known structures of this town (Fig. 8f) can be clearly recognised in the 1944 RAF flight, especially since invasive crops do not affect the hill on which the complex stands. In the case of the PAZ images (Fig. 5c), the result of the multi temporal analysis and the two-step application of pansharpening on the Sentinel-2 scene did not produce an outcome better than appreciating the contour represented by the walls with turrets of the villa. The olive tree cultivation system, taking advantage of the Roman terraces, makes it difficult to appreciate greater details even when performing various combinations with the Sentinel-2 bands. However, among the various analytics carried out, the ones that have provided the best results have been those applied to the LiDAR data. (Fig. 8 d and 8e). Thus, the enormous terraces on which the buildings were built are clearly acknowledged, giving greater insight into their dimensions and being able to appreciate that there may possibly have been two more terraces oriented to the opposite side of the hill (NE), as well as various structures that could have corresponded to the buildings of the complex.

3.3. Reviewing traces of the Roman parcelling system

Part of the fieldwork in Cosa was carried out by revising the Roman centuriation system, specifically the area that extends from the city to the Vall d'Oro. In an aerial photograph of the Royal Air Force (RAF) of 1944 Castagnoli (1993;789-790) already visualised elements of land division close to the Roman colony and established a first proposal.

As mentioned in the first section, one of these traces identified it as SDI. That is, within the land division system of a Roman colony, SDI was equivalent to the first land division located to the left of the Decumanus Maximus. Castagnoli verified this visualization with aerial photography on site, locating scattered materials in the area. Unlike the Decumanus Maximus or the DDI as examples, it is presently not possible to display this element in current RGB images.

The Sentinel-2 high resolution image was used to relocate the SDI parcelling element, once the pansharpening functions were applied in two steps using the PAZ image resulting from the multitemporal treatment as panchromatic. In the second step, various types of pansharpening, Bayesian and RCS were applied in QGIS, and Colour Normalized Spectral Sharpening in SAGA (Fig. 9). Image enhancement results were notable when performed with Bayesian and Normalized Spectral Sharpening but were affected by speckle-like noise in the RCS case. However, all of them presented distortions in the resulting colours, with RCS being the least affected and Normalized Spectral Sharpening the most altered. Among the group of Sentinel-2 images consulted, it was the one corresponding to April 18, 2022, which made it possible to highlight the persistence of this element of Roman parcelling division (Fig. 9). This anomaly was already clearly noticeable in the result obtained by applying only the Sen2Res function, so the second step of Pansharpening with the multitemporal image of PAZ had not altered it in terms of shape. On the other hand, the anomaly was barely visible in the multitemporal PAZ image, although it could be inferred in more detail in one of the PAZ scenes, specifically the one corresponding to September 12, 2019. The same trace was detected in another image from April 8, 2020 (Fig. 10).

On the other hand, the analytics carried out with the LiDAR data did not provide any positive results that would allow the relief of the pitches or centuriation walls to be highlighted.

3.4. A road from the XIX century?

One of the anomalies detected in the PAZ image obtained from the multi-temporary treatment was found in a North-South direction alignment located about 400 m Northwest from the still visible remains of the Decumanus Maximus (Fig. 11 a.).

Due to the type of anomaly detected and the similarities with the results obtained in previous works (Fiz et al., 2021; 16-19,20) in which infrastructures such as roads were more detectable in crop fields through images obtained with SAR, the review of the Tuscany Cadastre through the CASTORE server superimposed on the resulting images provided the possible explanation for this anomaly. This Cadastre, drawn up between the end of the 18th century and the beginning of the 19th century, shows a path that would be the evolution experienced by the Decumanus Maximus identified by Castagnoli and that had linked the colony of Cosa and the Via Aurelia with the interior of the territory. It is pointed out that the Cadastre has been obtained through the Castore WMS server, so it should be studied with the due precautions of a previous process of georeferencing historical cartography subject to errors. This section has been identified with the anomaly detected also due to the fact that in the Cadastre they indicate how at this point this section does not exactly pass along the margin of the cultivated fields but at a distance of about 40 m from the separation between fields and the beginning of the elevations (Fig. 11b). In other words, based on this, it could be assumed that the location of the anomaly would indeed coincide with the road documented in the 19th century cadastre.

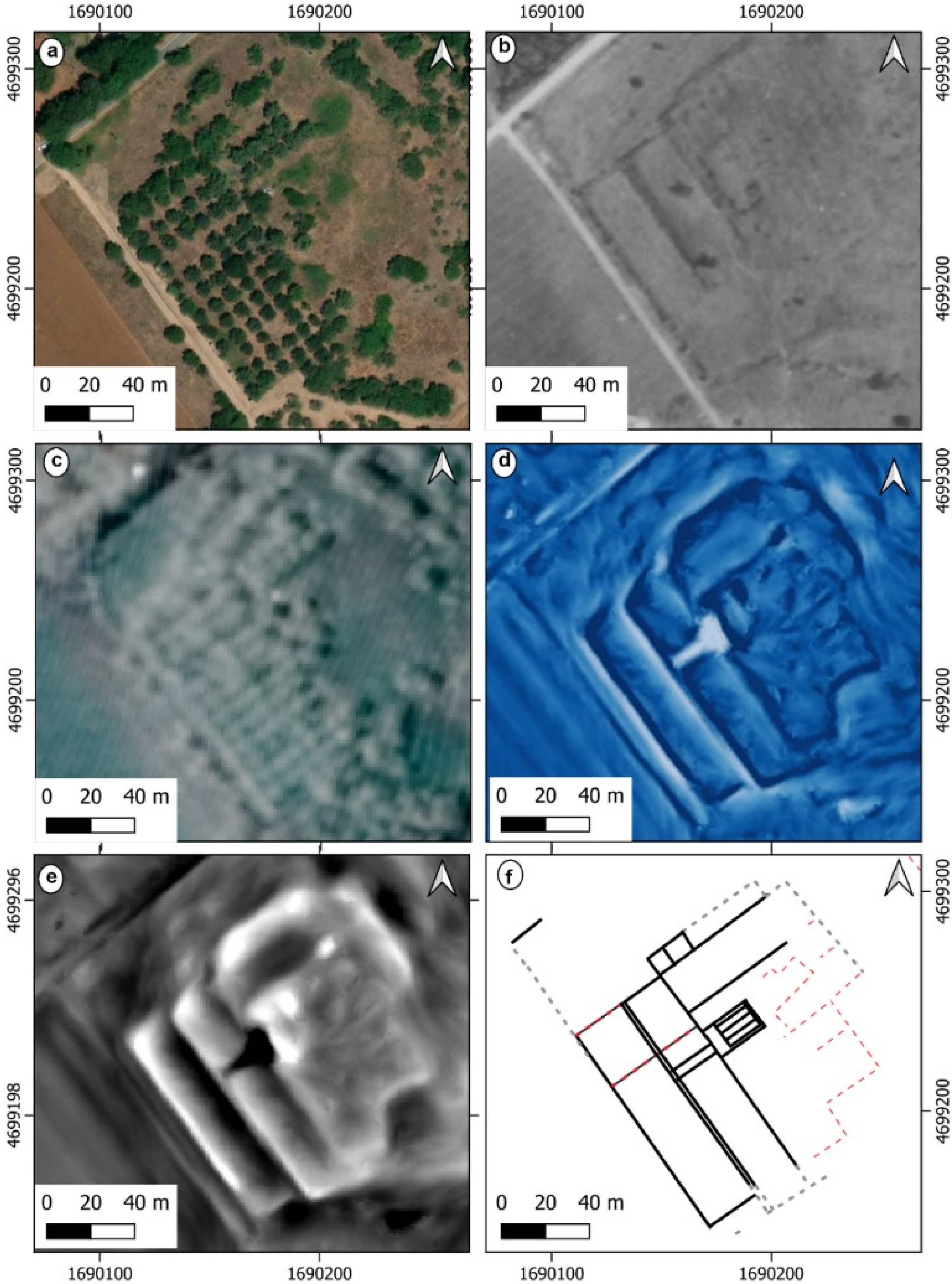

Figure 8: a) ESRI Satellite Image; b) RAF image of 1944 RAF 1944_135_448_4005; c) Sentinel-2 image (04/18/2022) after applying the two pansharpening steps, Sen2Res and Colour Normalized Spectral Sharpening Bands 8/3/2; d) Image combined from the treatment of OPEN-Positive (60% Transparency) and OPEN-Negative, obtained with the RVT programme on DEM LiDAR; e) Image resulting from the treatment of DEM LiDAR with the Simple Local Relief Model (SLRM) function; f) Structures of the villa delle Colonnette. Continuous and discontinuous black lines obtained from (Carandini, Cambi, 2002; Quilici & Quilici,1978)(26) and Dashed lines in red, identified from the analytics performed.

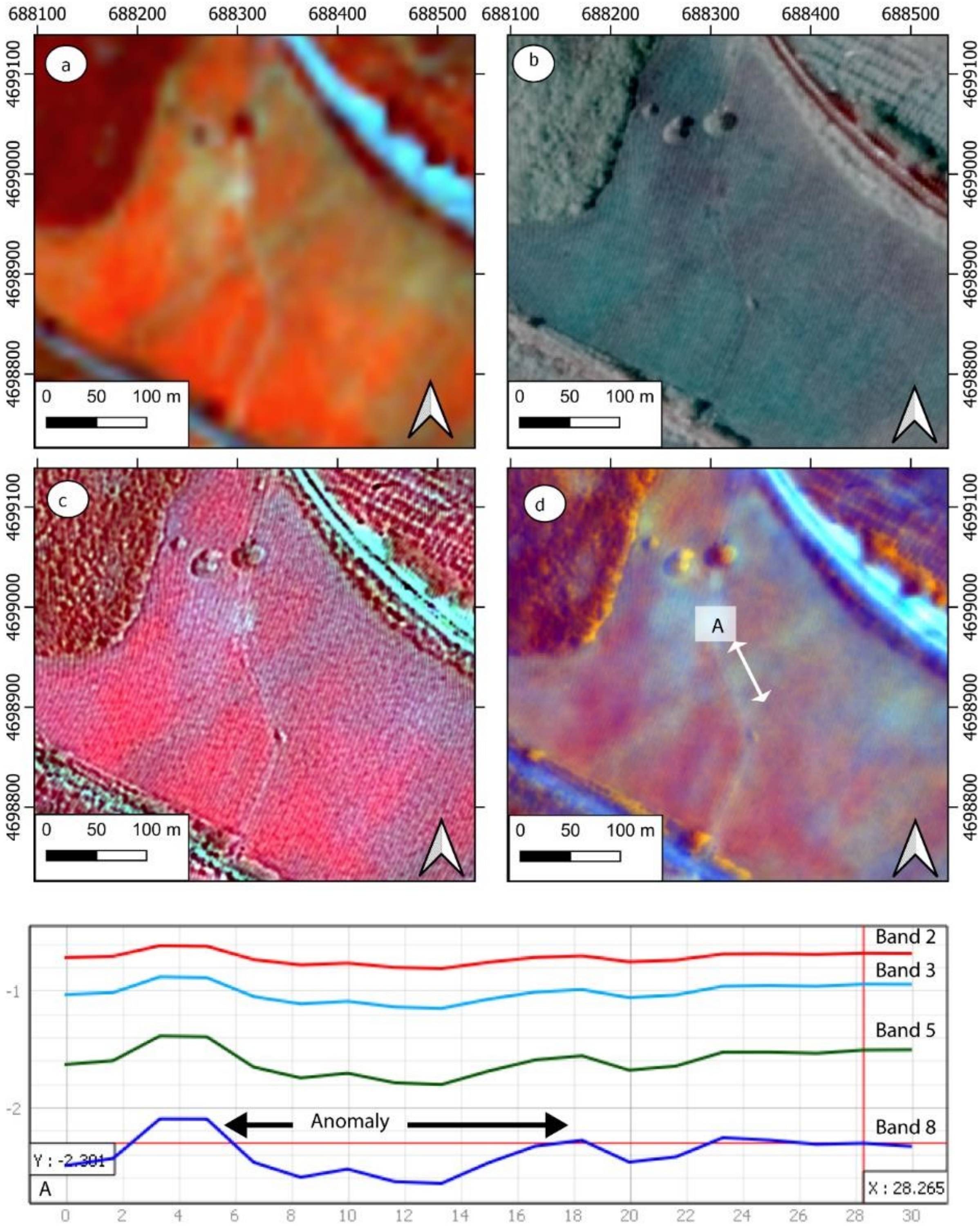

Figure 9: a) Sentinel-2 image from 18/04/2022 after applying the Sen2Res Bands 832 function; b) Sentinel-2 image after applying the two pansharpening steps, Sen2Res and Colour Normalized Spectral Sharpening; c) Sentinel-2 image after applying the two Sen2Res and RCS (Reaction Control System) steps; d) Sentinel-2 image after applying the two pansharpening steps, Sen2Res and Bayesian. A) Profie applied to the Sentinel-2 image after being pansharpened.

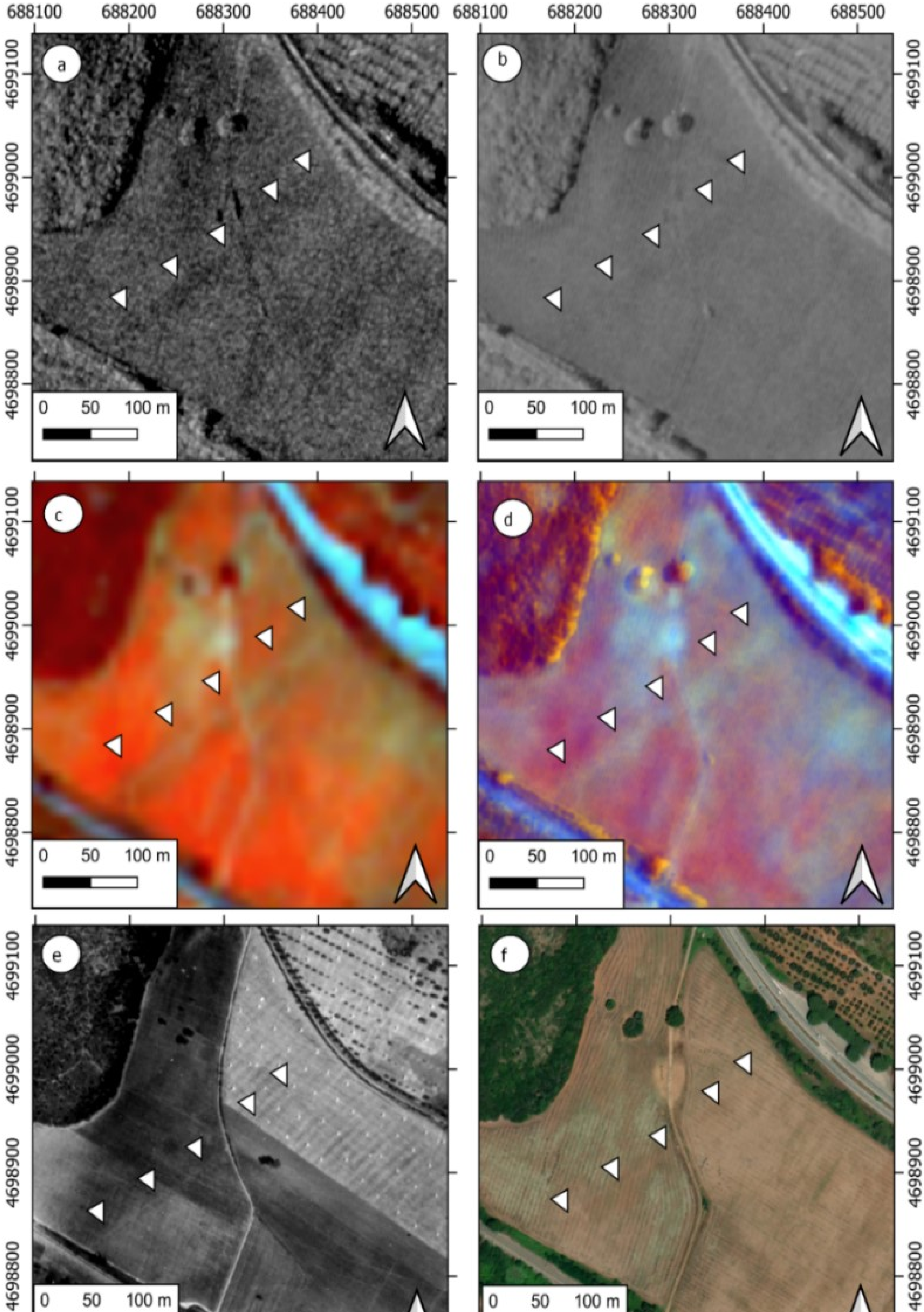

Figure 10: a) PAZ image from 12/09/2021; b) Image resulting from multi-temporary PAZ treatment; c) Sentinel-2 image from 18/04/2022 after applying the Sen2Res Bands 832 function; d) Sentinel-2 image after applying the two pansharpening steps, Sen2Res and Colour Normalized Spectral Sharpening; e) Royal Air Force flight, 1944; f) ESRI Satellite (ArcGIS/World_Imagery)

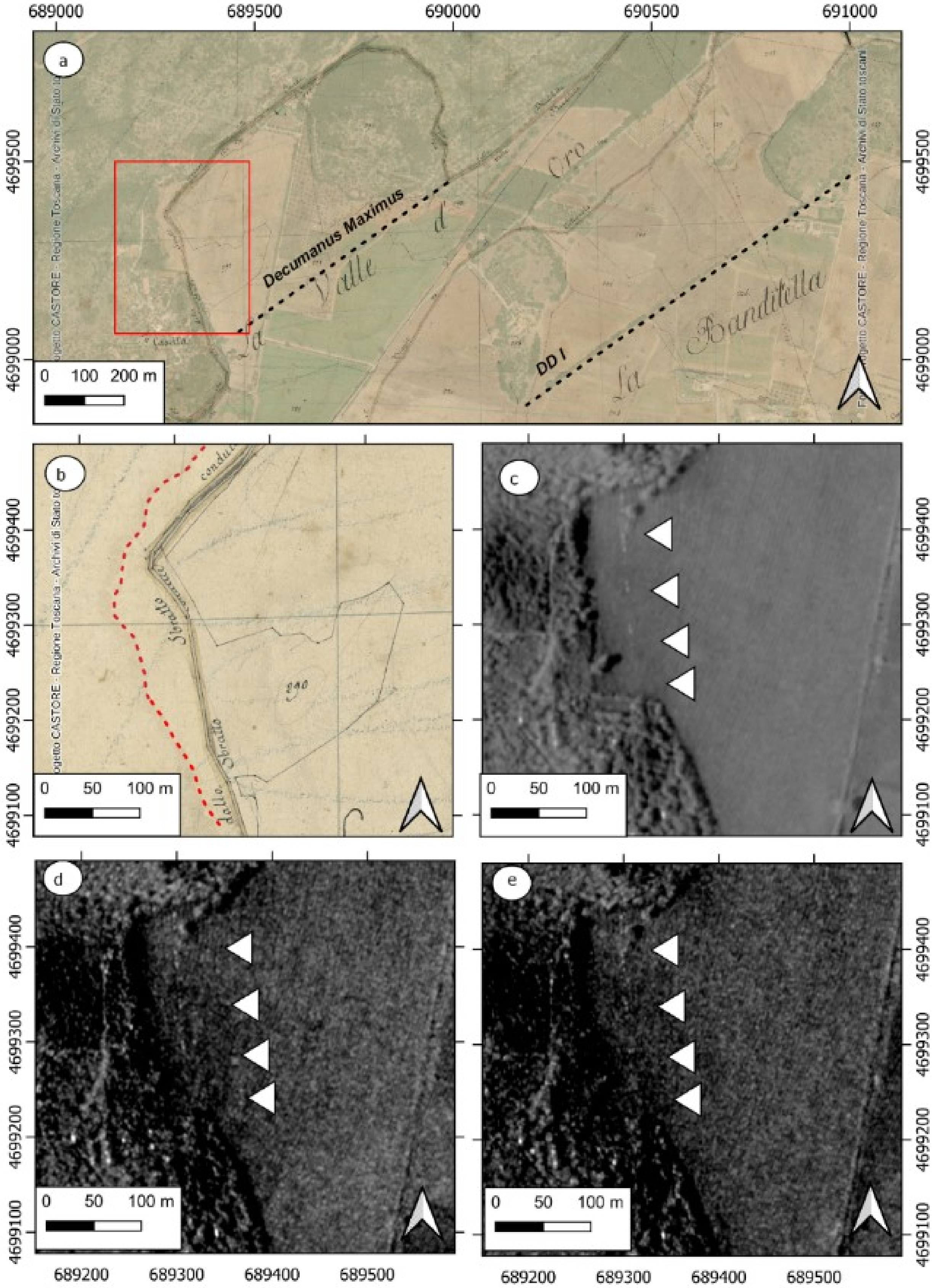

Figure 11: a) CASTORE WMS server (Castore, 2023). Image of the cadastre between the end of the XVIII century and the beginning of the XIX century. Transparent at 70% with the ESRI Satellite image (ArcGIS/World Imagery). Black dashed lines, Decumanus Maximus and DDI. Continuous line in red, display area of anomalies; b) Enlargement of the cadastre in the anomaly display area. Red dashed line, separation between elevations and fields delineated in the cadastre; c) Image resulting from the multi-temporal treatment of PAZ images; d) PAZ image from 09/12/2019 e) PAZ image from 27/08/2021.This anomaly appears in several of the individual PAZ images, such as those corresponding to 09/12/2019, 29/08/2020 and 27/08/2021 (Fig. 11 c, d and e).

The name that identifies this road in the cadastre is strada vic. Tagliata. A 60 m channel is known under the name Tagliata, which was excavated in the rock and has a 20 m high open section at one of its points.

Together with two natural canals, Spaco della Regina and Piccolo Spacco, it formed a system of fish farms connected by a canal to the fish factories in the lagoon, where the fish were processed and distributed through the small port connected to the Tagliata and the colony of Cosa (McCann, 1979; 397). The enormity and picturesque character of the space, together with the abandonment of Cosa, would explain why the XIX century road was named strada vic. Tagliata. The reason for this diversion would lead us to speculate on issues, such as rights of way in private property or issues related to the maintenance of a road in the context of Mediterranean climate, affected by intense seasonal rains, an orography that is likely to generate flood areas, and added to the lack in that period of an adequate water drainage system.

It should be noted that this anomaly continues to appear in the most recent PAZ images, specifically the one requested on July 23, 2022, with HH and VV polarisation (Fig. 12). The SAR image was also treated with the sharpening process, taking as panchromatic the multi-temporary image taken from the set of PAZ images only with HH polarization. The anomaly can be observed both visually and graphically (Fig. 12, profiles A and B).

4. Discussion

So far, the use of SAR images has had positive results in archaeological research in several environments. Thus, according to Stewart et al. (2013), SAR remote sensing has been successful in sand covered areas. On the other hand, Dore, Patruno, Pottier & Crespi (2013) argued that the characteristics of this type of SAR sensors (independent of the external light source, cloud cover of penetration zones or ground penetration) have extended the limits of acquisitions from optical satellites, and that the combined use of both types of sensors in archaeological research by remote sensing was advisable.

In addition, the use of SAR has had interesting results in non-arid areas with vegetation, as is the case of (Stewart et al., 2018) with the detection of archaeological forms, combining results of intensity and interferometry in SAR images. According to Monterroso and Martínez (2018), it is in the spaces of cultivated soils where it seems easier to interpret the SAR-X images in comparison with the more abandoned grounds, as indicated by Stewart et al. (2018.204-208) in the Portus of Ostia. Also, the interpretation of Monterroso and Martínez (2018) was maintained in cases in which periods of intense rain are observed, with soil moisture indices higher than the annual index. The impressions of Monterroso and Martinez were perceived and verified in this work, now using PAZ images and after obtaining positive results in the archaeological site of Clunia (Burgos) and its surroundings (Fiz et al., 2021) and always in combination with other LiDAR techniques or images from optical sensors.

The set of PAZ images were taken in summer periods and at the beginning of the Autumn season and in an area with wide contrasts between maximum and minimum temperatures and little precipitation. In this sense, it can be said that the meteorological conditions in which this study has been carried out are like those found in the Clunia study (Table 2).

The results obtained should be contextualized by emphasizing that the SDI Roman centuriation alignment (Fig. 9) is observed in an individualised PAZ image from September 12, 2021. It should be noted that the meteorological records of the Tuscany region have not indicated any rain on record between August 1st of that year, with a precipitation of 1 mm/m^2, and the 14th of September. In other words, the scene is captured at the end of a period of just over a month of high maximum and average temperatures and no rain (Tab. 2). Furthermore, the effectiveness in cultivated soils on a cultivated field in continuous care mentioned by Monterroso and Martinez should be recalled. In contrast, it is also of interest to observe that the weather records that contextualise the Sentinel-2 image of April 18, 2022, used in the same study, indicate slight rainfall from March 29 to April 9 and an increase in the maximum temperatures of almost 4º (Tab. 3). This is to say that a differentiation in the growth of the vegetation with the presence of an intrusive element is shown when observing the Sentinel-2 images with the infrared band. There is no doubt that this intrusive element would be the SDI centuriation wall seen by Castagnoli in the 1950s. This intrusive element is what marks a light-coloured longitudinal shape that contrasts with the intense red growth of the vegetation around it.

Table 2: Source data from the meteorological station of Capalbio (Tuscany Region). Settore Idrologico e Geologico Regionale (Archivio històrico della Toscana, 2022; Servicio OGC, 2023).

Month/Year	*T. Max*	*T. Min*	*T. Average*	*Prec. (mm/m2)*	*PAZ images involved*
Ag. 2019	34.9	16.4	30.2	2.6	1
Sep. 2019	33	13.2	26.9	160.8	3
Oct 2019	25.7	8.6	22.8	43.4	1
Jul 2020	35,1	15.9	30,9	5.4	1
Ag 2020	36,7	13.9	30,7	34.8	2
Jul 2021	34,8	15.4	29.9	3,2	3
Ag. 2021	35,7	14.1	29.7	1	2
Sep. 2021	30	27	13.6	0,6	2

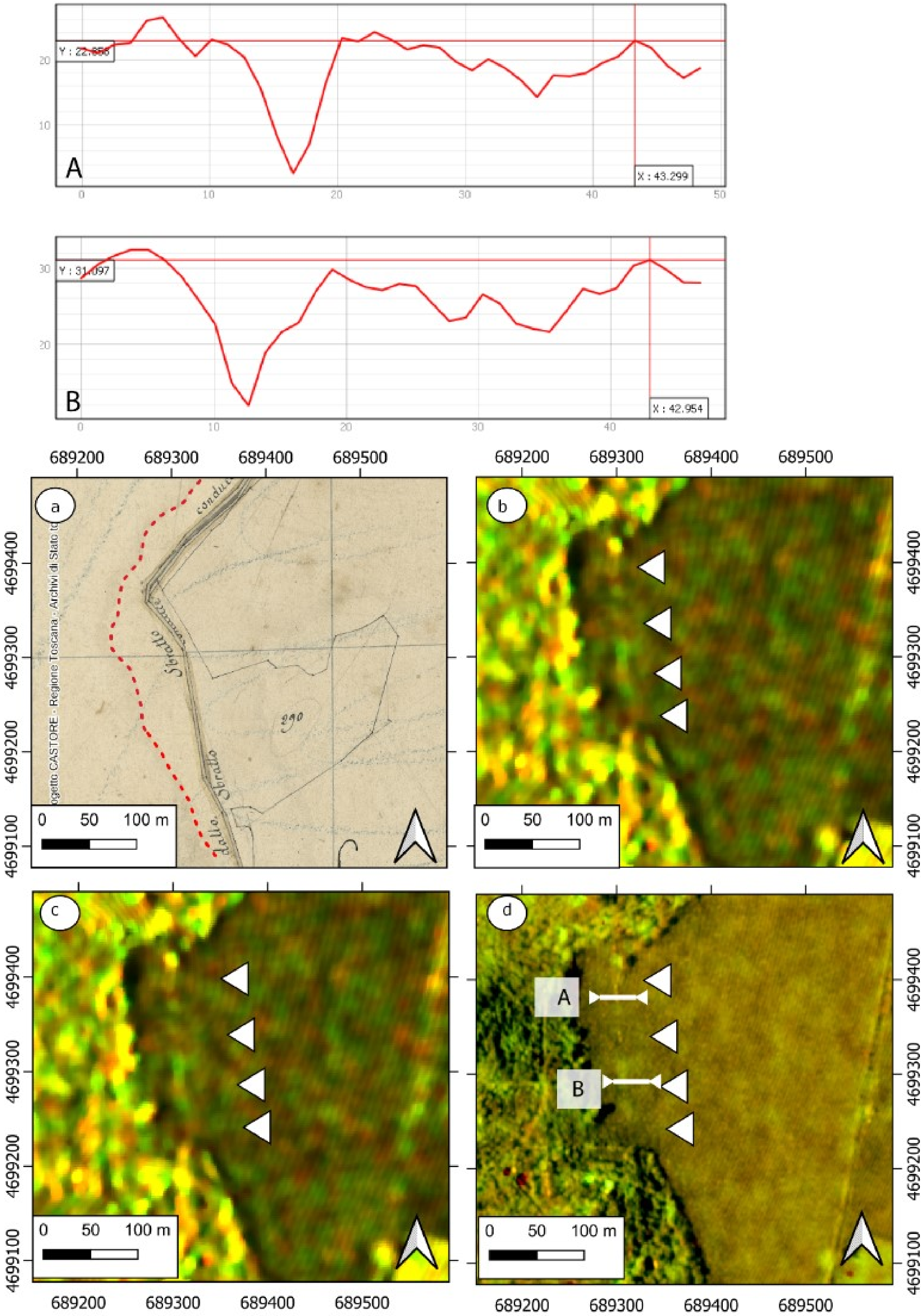

Figure 12: a) CASTORE WMS server. Image of the cadastre between the end of the 18th century and the beginning of the 19th century (Castore, 2023). Red dashed line, separation between elevations and fields delineated in the cadastre; b) PAZ image from 23/07/2022 HH and VV polarisation; c) Paz image from 23/07/2022 Polarisation VV; d) Result of the application of the IHS sharpening function of the SAGA programme using as panchromatic the image obtained from the multi-temporal treatment of the PAZ images. A) B) Profiles of PAZ Image from 23/07/2022 pansharpened from the multitemporal treatment of PAZ images.

Table 3: Meteorological context of the Sentinel-2 image from 18/04/2022 (Archivio històrico della Toscana, 2022).

Dates	*T. Max*	*T. Min*	*T. Average*	*Prec.*
29/03-09/04	14.85	6.24	10.54	56.2 mm/m2
10/04-18/04	18.51	6.8	12.6	0

The anomaly detected both in the multi-temporal treatment of the PAZ images and in the individualised images with HH and HHVV polarisation, which was identified as a 19th century path, was not observed in the rest of the analyses carried out to date with other data sources. It was not observed in the results of the analyses on the LiDAR images, nor was it detected in the treatments applied to the TripleSat or Sentinel-2 multispectral images. However, it is necessary to recognize that an exhaustive work has not been done for the moment.

In the case of the results of the *Villa delle Colonnette*, those obtained from the treatment of LiDAR images are certainly more definitive. In this case, the PAZ images allow the site to be delimited based only on the exterior terracing walls. The olive tree cultivation system observed in the images makes it difficult to distinguish any other type of archaeological anomalies, where in the case of the PAZ radar, as compared to other types of radar sensors, crossing is not allowed.

Finally, the outcome of the proposal to use the results of the multi-temporal processing of SAR images to apply sharpness functions on Sentinel-2 type medium resolution multispectral images allow for a positive reaction – a proposal that had already been made by Ehlers (2008) and which is also amplified to treating the PAZ images themselves with double HH and VV polarization (Fig. 12). The sharpening functions that were applied, however, suffer from the problems that Klonus et al. (2008) cite in their works, proposing a fusion system that can currently be used, albeit only in commercial software, ERDAS, to which there was no access. It must be considered, however, that in recent years other directions have been proposed to be taken into account, such as the super-resolution of spectral images with neural networks and deep learning (Mei, Jian, Li, & Du, 2020; Müller, Ekhtiari, Almeida, & Rieke, 2020), which are intended to be addressed in the future.

5. Conclusions

With the results obtained in different tests, it is possible to confirm that the multi-temporary treatment of SAR PAZ images provides better results than an individualised analysis of the image. The process of eliminating speckle from this type of data source is much more effective with multitemporal treatment, obtaining sharper images. The results have proven its effectiveness in two different archaeological environments, such as Clunia (Burgos, Spain) and the territory of Cosa (Ansedonia, Italy). It is necessary to review individualised images only in certain cases since the system that uses this process can dilute the resulting effects.

As other authors have already pointed out, it is clear that a non-invasive study of these characteristics must be carried out with several data sources, as has been done in this study, since all the possible results can complement and explain each other. For example, in the present case, the use of DTM-LiDAR, once enhanced with the RVT program functions, did not give positive results with the SDI centuriation limit. However, PAZ did produce positive results once the multitemporal treatment was applied. These are in addition to what was suspected in maximum resolution Sentinel-2 images (10 m/pixel) provided by Sentinel-2. As observed, the use of PAZ as an image for pansharpening with the Sentinel-2 images further reinforced the positive anomaly character of the SDI boundary.

Finally, the next step was using new technologies to verify the results of studies, in which it was only possible to resort to prospecting on the ground and analogical aerial photography in black and white, such as the proposal for centuriation of the territory of Cosa made by Castagnoli. In this case, the SDI structure was seen, which Castagnoli observed in the aerial photography, but of which he only located materials on the ground. This has been visualised both in individualised PAZ images and in the Sentinel-2 image with increased resolution, using as panchromatic the image result of the multi-temporary treatment of PAZ images.

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