Remote Sensing Techniques in Archaeology. From Space to Ground Investigation through the Microwave Spectrum: SAR and GPR Detection.

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Abstract. The present research deals with the possibility to detect surface and subsurface archaeological structures by means of satellite SAR (Synthetic Aperture Radar) full-polarimetric data of ALOS PALSAR sensor and GPR (Ground Penetrating Radar) prospection of the soil. The archaeological sites of Veio (an Etruscan-Roman site 10 km North of Rome, Italy) and Aquino (an ancient Roman city in the Southern Lazio, Italy) have been selected for the study. The main goal of the research is to find a complementary non-invasive technique for archaeological investigation to be considered as a preliminary step for the detection of ancient structures, possibly to be used before any dig campaign start. The analysis of ALOS PALSAR products has been compared to optical images and to cartographic data as well, and then validated with the GPR prospection, in order to confirm what observed from satellite, both for well known archaeological marks and for assumed underground structures. Ancillary information (meteorological conditions, geologic maps, archaeological maps) and surveys in situ constitute a comprehensive critical and scientific approach for data interpretation. The work, still in progress, aims to define and propose a methodology based on the integration of information extracted from both SAR satellite and ground radar signals over different archaeological landscapes, providing a complete overview of the microwave portion of the spectrum.

Keywords. Archaeology, optical data, Synthetic Aperture Radar, Ground Penetrating Radar.

1. Introduction

Since the past century, remote sensing contribution for the archaeological research has been proved, as attested by the employment of the first historical military aerial photography for the observation of underground ancient cities. Detected soil anomalies were thus registered and quoted in the cartography. Presently they are investigated also by means of high-resolution satellite images, thus providing an updated overview of the supposed underground archaeological structures remotely identified and a continuous discovery of new archaeological complexes.

Underground archaeological structures (if not too deep) influence the regular vegetation growth, displaying some anomalies in the surface ground patterns as colour, height, state of health of grass (vegetation anomalies) or affecting the soil moisture content in that point and in the surrounding area (moisture anomalies) [1].

This is why satellite optical images can provide the same results of the aerial ones. However, the advantages of SAR images used in this research are linked to their higher amount of information
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(despite the lower spatial resolution): polarimetric information and 24-hours observations independent from Sun illumination and meteorological conditions [2].

Ground surface geophysical prospecting methods are, as well, progressively used for archaeological sites investigations, as they provide a physical and geometrical reconstruction of underground structures. As known, GPR acquisitions provide high-resolution data with the aim of reconstructing a global overview of the subsoil within the area investigated [3].

The two selected test sites are located in Italy. Both the sites are well known areas from an archaeological point of view, thanks to the previous studies of aerial photographs and photogrammetric restitution already carried out by Lecce University (Italy) and then confirmed by some test-excavations [4]. We used these previous studies and the optical data set available as a basis for the analysis of SAR products.

The optical data set used was composed of one KOMPSAT – 2 image; one ALOS (Advanced Land Observing Satellite) PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) image and two PALSAR (Phased Array type L-band Synthetic Aperture Radar) quad-polarization images [5].

The processing package PolSARpro [6], developed and distributed by the European Space Agency (ESA), was used for polarimetric SAR processing. Images were provided through the online catalogues Earth Observation Link (EOLi) [7].

GPR surveys have been performed by ITABC-CNR employing a SIR 3000 system (GSSI), equipped with a 500 MHz bistatic antenna set to a constant transmitter-receiver offset in both the sites.

2. Methods

2.1. Study areas

Aquino Roman town (41°29’59.06’’N 13°41’27.34’’E UTM WGS 84) is located in the Southern Latium region. It arose between the IV and the III century BC and then became a late Republican Roman colony developed until the Lombard conquest in the V century AD.

The ancient Etruscan-Roman city of Veio (42°00’47.43’’N 12°24’29.26’’E UTM WGS 84) is located at about 10 km North of Rome in the archaeological Park of Veio. The city arose in the
VIII century BC and reached its maximum glory in the VI century BC with the Rome conquest, until its slow decline in the I century AD (Fig. 1)

Concerning Aquino analysis, a KOMPSAT-2 panchromatic image (1 m spatial resolution) has been used as a basis for the georeferencing process of all the ALOS PALSAR processed products; in the case of Veio, the optical basis used has been an ALOS PRISM panchromatic image (2.5 m spatial resolution).

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2.2. SAR processing

ALOS PALSAR products have been chosen because of the polarimetric capability of its sensor. Polarimetry is a technique based on the full vector nature of polarized electromagnetic waves. The backscatter response of full-polarized signals contains a high amount of information extracted from the four different type of wave polarization: HH; HV; VH; VV. The analysis of these combinations of transmitted and received polarization constitutes the science of radar polarimetry. By using polarimetry, it is possible to discern the nature of the scattering mechanism coming back to the sensor: single bounce, double bounce and volume scattering [8].

The processing of the two ALOS PALSAR images, performed with the PoIsARpro ESA free tool, consisted, first of all, in the extraction of the T3 matrix elements. Then, Entropy and Alpha Angle products were computed. Entropy determines the degree of randomness of the scattering process, while Alpha angle values can be related with the physics behind the scattering process [9].

To better understand the percentage and the type of the scattering mechanism over the area, a Freeman Decomposition has been performed as well.

The polarimetric products obtained have been subsequently georeferenced, after the creation of a slave image (average of diagonal T3 matrix elements T11, T22, T33), having as master image the 1 m panchromatic KOMPSAT-2 image in the case of Aquino, and the 2.5 m panchromatic ALOS PRISM image in the case of Veio. The archaeological maps were georeferenced as well.

2.3. Ground Penetrating Radar survey

Ground Penetrating Radar technique, more and more used for archaeological sites investigation, has been chosen as validation method.

A GPR survey has been performed in the two sites employing a SIR 3000 system (GSSI), equipped with a 500 MHz bistatic antenna set to a constant transmitter-receiver and with horizontal spacing between parallel profiles of 0.5 m. The 500 MHz antenna was considered to be the more suitable for this kind of survey, in order to have a good compromise between wave penetration and spatial resolution and thus define the supposed archaeological structures of interest.

One important parameter to be considered in organizing a GPR prospection is the geology of the area. The bedrock of the archaeological area of Aquino is characterised by travertine rock layer about 15 - 18 m thick. These units lie on a series of Miocene-Pliocene sand and clay sediments. The travertine rock is covered by a surface soil layer about 0.30 – 0.50 m thick [10].
The bedrock of the archaeological area of Veio is, instead, characterized by a series of lithoid tuffs, with average resistivity values of about 30-80 $\Omega \cdot m$. These units are about 10 m thick and they lie on Pleistocene-Quaternary sand and clay sediments. These lithoid tuffs are covered with a layer of top soil of about 0.20 m and 0.30 m [11].

3. Results

3.1. Case study: Aquinum (Frosinone), Italy

Polarimetric products of ALOS PALSAR image has been overlapped to the KOMPSAT-2 panchromatic band and to the archaeological map. Red features in the map stand for archaeological structure, while the investigated area is circled in red. (Fig. 2)

In this way it has been possible to identify the studied area, well distinguishable in the optical data, in Entropy and Alpha Angle products (Fig.3).
The portion of the field investigated both with SAR and GPR prospection is the northern part of the area. It is visually characterized by different pixels colour (as the southern portion) respect to the remaining area (Fig. 3). Each pixel value was analyzed and an average between them was performed. The values for Entropy and α Angle are, respectively 0.58 and 22°. The degree of randomness of the scattering process (Entropy) and the physics behind the scattering process (α Angle) were then identified in the segmentation of the H/α plane (Fig. 4).

The values observed in the upper part and in the lower one are coincident with the area in which underground structures are supposed to be, according to the reconstructed urban organization seen from historical aerial photographs by archaeologists.

It has been noticed, by crossing H and α values, that the principal scattering mechanism occurred is a Surface Roughness with Propagation Effects mechanism, positioned in the Zone 8 of the H/α plane (Fig. 4).

The subsequently performed Freeman decomposition validated the identified scattering as a single bounce type.

Few days before the PALSAR sensor acquisition, the field was plowed. After plowing, the field surface was made up of terrain mixed to ancient broken travertine blocks coming from underground structures. This could be the reason of the surface roughness seen by the SAR sensor, although the field surface is a flat surface.

The GPR survey has been performed only in the northern part of the field as a validation of the results visualized by Entropy and Alpha Angle products (Fig. 5).
GPR products are constituted by several *time-slices* representing soil anomalies detected at different depth, as the electromagnetic wave goes through the ground. A 500 MHz antenna, as the one employed in this research, allows the electromagnetic wave to penetrate in the ground till 2 meters depending on the soil characteristics. The considered *slice* refers to the first 30 centimeters of the ground. Several black responses, that underline the presence of underground structures, can be noticed as a series of E/W oriented walls and rooms’ perimeter (Fig. 6).

![Figure 6: GPR time-slice at the estimated depth of 0.30 m.](image)

The archaeological interpretation of the detected anomalies can be confirmed by the accordance with the already observed and studied ancient urban organization of the Roman *Aquenum*. In fact, some of them have been identified in the area where they were supposed to be by archaeologists.

To validate and compare GPR acquisition with SAR data, Entropy and $\alpha$ Angle products have been overlapped to GPR slice (Fig. 7).

The integration of GPR and SAR data shows a certain correspondence between the registered Entropy and $\alpha$ Angle values.

![Figure 7: GPR slice overlapped to Entropy and $\alpha$ Angle products.](image)

Taking into account the different spatial resolution between these two radar acquisitions, it has been difficult to identify with extreme precision GPR anomalies on SAR products, but it has been possible to observe a correlation between the anomalies detected by the two methods.
3.2. II case study: Veio (Rome), Italy

Concerning Veio, the same methodological procedure of Aquino has been applied. The ALOS PALSAR image has been georeferenced using as a basis the panchromatic ALOS PRISM image acquired on the 25 July 2009, and then overlapped to the archaeological map: red features stand for archaeological marks; the investigated area is circled in yellow (Fig. 8).

![Figure 8: ALOS PRISM image of Veio. Archaeological map, (after Guaitoli, 2003)](image)

The research has been carried out in “Piazza D’Armi” area of the archaeological site. The polarimetric image has been processed extracting the Entropy and \( \alpha \) Alpha values first, then performing a Freeman Decomposition in order to validate the scattering mechanism.

Observing the RGB Freeman decomposition product (Fig. 9), as a first indicator of the scattering mechanism occurred, the whole SAR investigated area indicated a single bounce and some of the volume scattering wave response, represented respectively by the Blue and Green channel (Red: Double bounce), as the major types of scattering of the area.

![Figure 9: ALOS PRISM image of Veio. Freeman decomposition.](image)

The analysis of Entropy and \( \alpha \) Angle products confirmed a coherent response in the whole area (Fig. 10).
The identified scattering mechanism could have been caused by a particular characteristic of the soil, probably due to underground archaeological structures which affect the soil surface. The upper part of Piazza D’Armi hill (in yellow circles) is the one investigated with GPR prospection (Fig. 11).

As can be seen, the orange anomalies, identified by GPR prospection, are corresponding to some underground structures previously identified through aerial photographs and to others unknown archaeological marks.

The lower part of Piazza D’Armi area is a private plowed field in which archaeologists observed through aerial photography, some soil anomalies due to underground structures, but neither dig campaign nor GPR surveys have never been undertaken.

Being the observation of Entropy and $\alpha$ Angle values corresponding to a surface scattering, both in the GPR investigated northern part of the hill and in the southern one, and being the presence of underground structures ascertained thanks to historical aerial photographs also in the southern field,
also this area is supposed to have a similar GPR response. Planned GPR surveys will be performed in the area to validate or not the mentioned SAR results.

4. Conclusion

The purpose of the research has been the comparison between two different radar acquisition methods, as satellite Synthetic Aperture Radar and Ground Penetrating Radar are.

Being this an ongoing study, the presented results give first a overview of the potentiality of a comprehensive scientific approach applied to a humanistic field of research as Archaeology. In the case of the Roman site of Aquino, GPR data validate the anomalies observed by the SAR sensor; in the case of the Etruscan-Roman site of Veio, they give an initial validation for the identified underground structures to be widely confirmed.

This still ongoing investigation will be carried on with already planned GPR acquisitions over the whole areas. The survey’s products will be then integrated with SAR polarimetric data at a higher spatial resolution. The integration supplies the other sources to which radar should always be compared: optical data, aerial photographs and cartography.

The only ALOS PALSAR polarimetric image used (one for each site) was restricting for a univocal interpretation of the anomalies. A comparison among several images acquired over the same area is necessary. Differences in SAR and GPR spatial resolution (ca. 20 m vs few centimeters) has been a limit for the study as well. That’s why in the future development of this research, TerraSAR-X data will be employed to test the continuity of the electromagnetic signal from air to ground.

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References


